AN ABSTRACT OF THE THESIS OF

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Title: Computer Assisted Design Of Humidification Equipment

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A computer assisted design model, developed for undergraduate students to teach the basic principles of humidification design, is developed and presented. Beginning with the development of the differential equations, the conversion to numerical code is presented, followed by a series of applications to mechanical draft cooling towers, natural draft cooling towers, and packed columns. Extensions of the program to other uses is also discussed. Several calculation options are presented which allow students to understand the effect of design options at a practical level. A user's manual, flow charts, program listing, and other design information are also included.

Computer Assisted Design of Humidification Equipment

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I. INTRODUCTION

Before the 20th century, slight consideration was given to the design of an industrial cooling tower or humidifier compared to the time and effort spent preparing plans for the rest of the plant. Water and air were comparatively abundant and essentially free; cooling towers were inexpensive and common wood construction, and the scale of industrial plants was not large, so the slight modification required to install familiar, reliable cooling tower equipment which had been in widespread use for many years was a relatively simple task.

The industrial revolution, coupled with the general availability of electricity in the early 1900's, quickly created the need for improved design techniques for industrial processes. As plants became larger and larger, the need for large capacity cooling towers grew rapidly. Today, in a 2000 Megawatt power generation station which runs cooling towers, cooling water for steam condensation circulates at rates greater than 60 m3/sec., and 3-4 liters of makeup water are required per hour per kilowatt to make up for evaporation losses (Singham, 1967). Ironically, the relative low cost of water has created an additional problem: as the demands on cooling have increased, and as energy costs continue to rise, companies cannot afford wasteful cooling tower designs, placing great pressure on the cooling tower industry to develop highly efficient contacting equipment.

Tower Description

A cooling tower is a structure whose general function is to remove energy in the form of heat by passing a gas, usually air, countercurrent to the liquid. The liquid enters at the top of the column and falls by gravity alone onto a packing material called fill. The gas, forced into the bottom of the column by fans, flows upward through the fill and exits at the top of the column, which is usually open to the environment. The bottom of the column is described as position 1, the top as position 2. A schematic of a tower showing all the symbols and conditions of the streams is given on Figure 4, page 19.

Historical Background : The Merkel Model

The major contribution to design and performance evaluation techniques is attributed to F. Merkel, who in 1925 outlined a set of design criteria which form the basis for cooling tower performance and design today (Merkel, 1925). Although the specific details of his technique are now considered to have only historical importance, Merkel's approach combined theory with empirical data so well that his technique still forms the basis for contemporary design.

Merkel's analysis combined sensible and latent energy transfer into a overall process based on enthalpy potential as the driving force. According to Merkel, each element of water in the tower is surrounded by gas, to which energy is transferred through the interface both by the direct transfer of convective energy as well as from the heat of evaporation as mass transfers from the liquid to the gas. Combining the process into a single equation,

$$Ldt = KadV(h'-h) = Gdh \qquad 1.1$$

and integrating, Merkel obtained a design equation which could be applied directly to the design of a piece of equipment:

$$\frac{KaV}{L} = \int_{TL1}^{TL2} \frac{dt}{h'-h} \qquad 1.2$$

KaV/L has been termed the capacity coefficient or tower characteristic; appendix A1 defines all of the variables developed in this and subsequent sections.

The development of this equation is based primarily on three assumptions (Baker et al, 1952):

(1) Evaporation losses in the energy balance equation are neglected (i.e., L is constant);

(2) The temperature difference between the bulk water and the interface is ignored; and

(3) There is assumed to be no resistance to mass transfer from the bulk water to the interface.

Although the assumptions and simplifications that Merkel employed in the development of the equations are now considered substantial, the elegance of Merkel's derivation lay in its ability to combine theory with empirical data. As the graphical expression given in Figure 1 shows, equation 1.2 conforms to the transfer unit concept in which the transfer unit corresponds to the size of a piece of equipment which would allow equilibrium to be attained. The integrated value corresponding to a given set of conditions is the number of transfer units NTU, a measure of the degree of difficulty in attaining equilibrium for a given set of conditions. Combined with a set of information about the contacting arrangement and relative flows of the two streams, equation 1.2 can be solved by mechanical integration.

The counterflow cooling diagram corresponding to the integration of equation 1.2 is found in Figure 1. Water

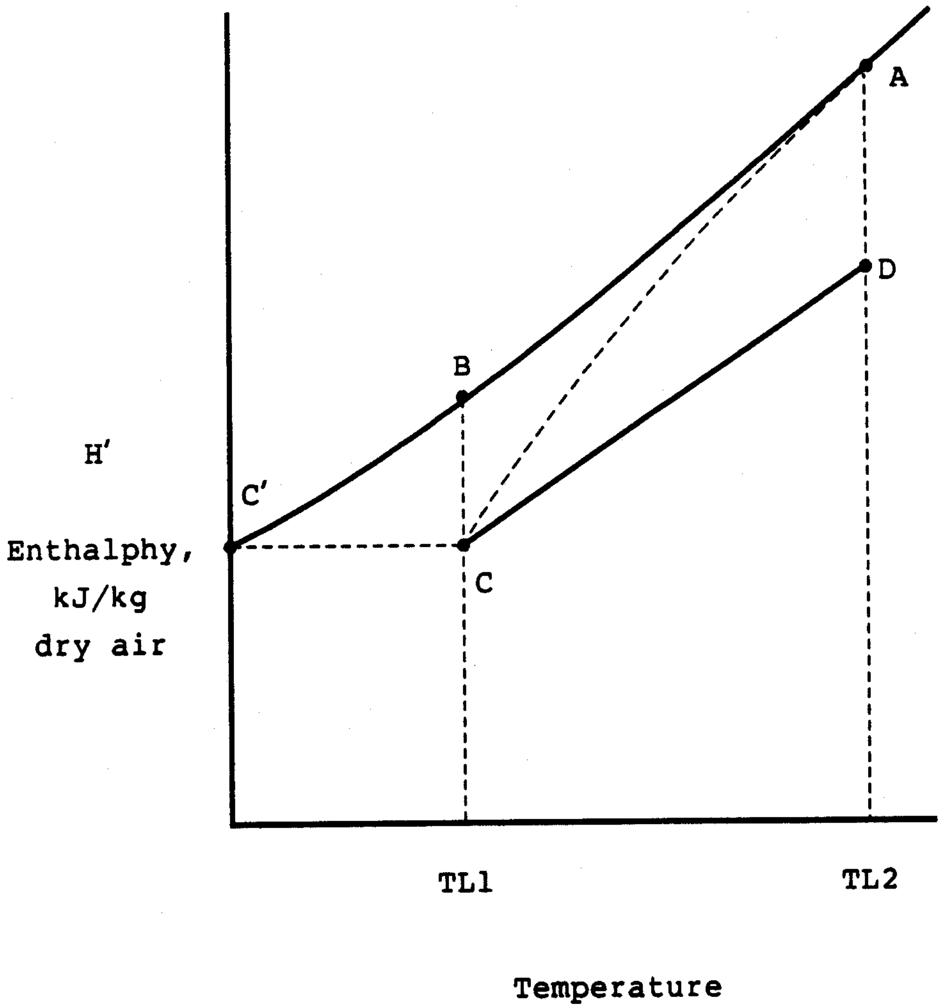


Figure 1. Enthalpy-temperature counterflow cooling diagram.

enters the tower at temperature TL2, surrounded by an interfacial film of saturated water vapor at the bulk water temperature, corresponding to point A. As the water is cooled to TL1, the film vapor enthalpy follows the saturation curve to point B. Air entering the bottom of the tower has an enthalpy corresponding to point C', and a vertical line drawn at any point such as BC represents the enthalpy difference between the saturated interface and the bulk gas stream. The straight line between points C and D represents the enthalpy of the bulk gas stream as a function of the liquid temperature at the same location in the tower, the slope of which equals the L/G ratio; the gas exiting the tower leaves at a point directly below A. L is assumed constant.

Cooling towers are specified in terms of water inlet and exit temperatures, as well as the inlet air temperature and the average humidity, but a given set of temperature conditions may be achieved by an infinite range of theoretical L/G ratios, shown diagrammatically in Figure 2. The imaginary situation corresponding to an infinite air rate (L/G=0) is represented by a horizontal operating line CD_0, and as L is increased, the slope of the line CD increases, decreasing the enthalpy driving force. The maximum L/G ratio for a given set of conditions is represented by an operating line that terminates on, or becomes tangent to, the saturation curve, CD_4.

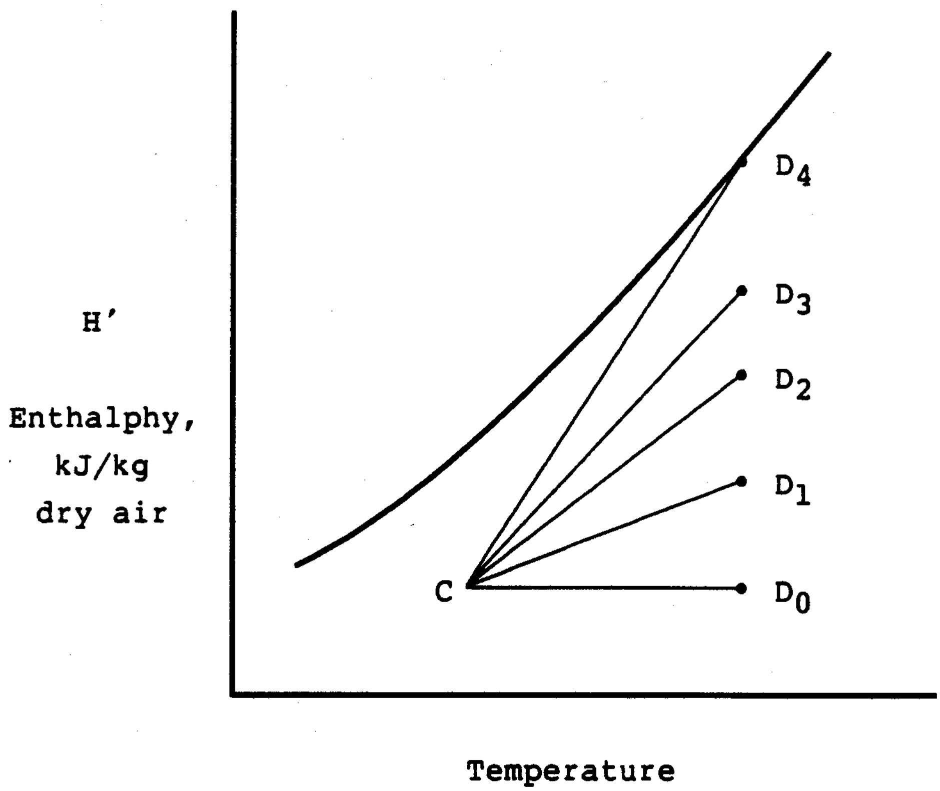


Figure 2. Various L/G ratios on an enthalpy-temperature diagram.

For a given L/G ratio, therefore, from a diagram such as Figure 1, equation 1.2 could be integrated graphically to determine a unique capacity coefficient; this coefficient Merkel termed the required coefficient. As L/G is varied, furthermore, a series of lines such as those marked CD_0, CD_1, and CD_2 in Figure 2 could be plotted, each supplying a new KaV/L from integrating equation 1.2, and by repeating these calculations a plot can be made relating the required coefficient to the L/G ratio. Figure 3 demonstrates such a plot.

A second line is also plotted on Figure 3, which is called the available capacity coefficient. The available coefficient was determined empirically from performance data, and was also available as a function of L/G. Plotting the required and the available coefficients on the same graph resulted in an intersection corresponding to the L/G ratio at which a given tower would operate at the design setpoints. Annual fluctuations in entering gas conditions or process liquid flowrates could be incorporated into the plot, yielding an estimate of the range of environmental conditions under which a tower being proposed could be expected to operate.

Although Merkel's approach was widely accepted as having adequately incorporated theory into cooling tower design, it had several drawbacks beyond those already

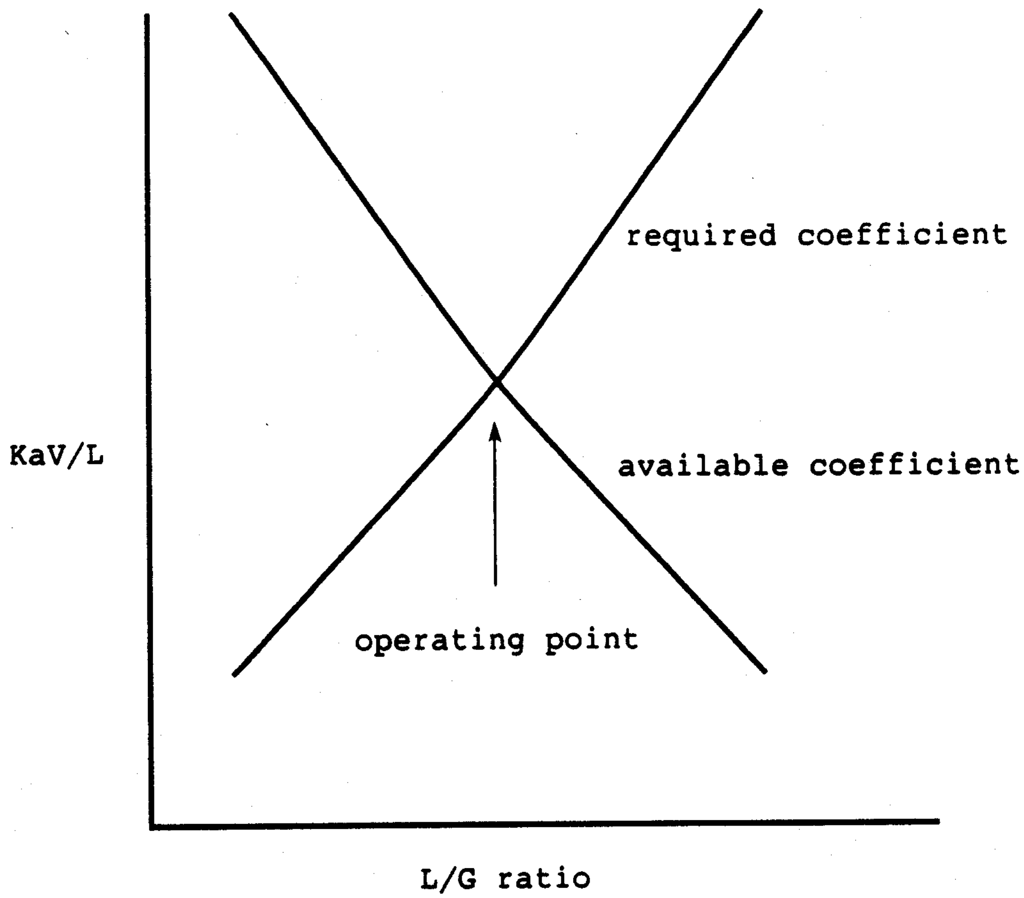


Figure 3. Tower characteristic, KaV/L, versus the L/G ratio.

listed. First, although it was already simplified theoretically, computationally it was very time consuming. Each point on the required curve corresponded to a tedious graphical integration of equation 1.2, and although the available coefficient curve is shown as a smooth curve, empirical data always display a surprising variance. The addition of daily, seasonal, and year-to-year environmental changes adds further complexity to the performance analysis, and although such effects could be incorporated into the required coefficient curve, empirical data had to be available in order to plot a corresponding available coefficient.

Aside from the theoretical simplifications incorporated into the model, the biggest drawback to Merkel's work was that since the available coefficient was based only on empirical data, it could only be applied to the development of units fundamentally similar to existing units. The creation of an available coefficient curve implied that the tower being designed would respond in the same manner as a prototype. Available coefficient data could only be obtained from units which had performed under known field conditions, so there was no way to predict how a tower would react to a set of new conditions. Similarly, new designs could not be evaluated until a test model had already been constructed and run, and even then the data from a scale model could not be extrapolated to a full size model without incorporating a safety factor which was so large as to make the design uncompetitive.

Efforts Since Merkel

By neglecting the resistance to energy transfer to the interface, Merkel's equations avoided the need for the explicit determination of an energy transfer coefficient. By summarizing KaV/L data as a function of the L/G ratio, the cooling tower industry avoided directly calculating individual transfer coefficients, although they lie at the heart of simultaneous energy and mass transfer calculations. In the decades that followed Merkel's presentation, efforts were directed at the development of equations which could predict capacity coefficients directly from L/G ratios. J. Lichtenstein, a great proponent of Merkel's ideas and the individual responsible for their widespread acceptance, in 1943 published a correlation to predict KaV/L as a function of L/G derived from data collected with a six inch by nine inch wooden test tower (Lichtenstein, 1943). Several other such correlations followed, and by 1950 Treybal summarized several of the available correlations for general use, including Lichtenstein's. Correlations developed for some of the standard cooling-tower fill arrangements are generally available and are still used today (Treybal, 1980).

Although the academic community favored the development of correlations for mass and energy transfer coefficients, the need existed to develop equations which were based on dimensionless groups, free from the limitations of a particular contacting device. Treybal (1980a, page 189) reflected the need in his statement that: "Despite the relative simplicity of these systems in that concentration gradients reside entirely in the gas phase, there are surprisingly few data for general design purposes", which he attributed to the difficulty in obtaining accurate data. That the industrial sector felt that such generalized correlations and the academic approach were of little value is well expressed by the lack of published commercial design articles in this area.

The development of high speed computers eased the computational difficulties associated with the Merkel techniques, and sophisticated proprietary design programs are now capable of every aspect of cooling tower design, including choosing from various tower models, simulating process conditions, laying out structural designs including blueprints, producing materials lists, and evaluating the economic factors in a new design (Baker, 1984). Contemporary design combines the results of such programs with vendor experience and advice in meeting the needs of potential customers.

Although the academic community has not needed to develop the comprehensive design programs heavily used by the private sector, the ability of computers to simplify tedious computations has prompted a reexamination of many of the assumptions and simplifications previously incorporated into design and performance analysis techniques, particularly the Merkel method. Nahavandi and Oellinger (1977), for example, reviewed the assumptions in the Merkel technique as they apply to counterflow equipment, claiming that errors due to the simplifications may result in non-conservative design errors as large as 12%; a similar review applied to crossflow equipment predicted errors as large as 20% (Nahavandi and Serico, 1975). Others have focused attention on the capacity coefficient (Baker and Hart 1952), errors introduced due to non-ideal liquid and gas flows (Onda et al, 1959), prediction and elimination of fog formation (Arefyev and Avekiyev, 1979), and errors induced by daily, seasonal, and microenvironmental variations in geographical specification data (McKelvey and Brooke, 1959).

Analytical programs free of the Merkel simplifications, however, face the problem of requiring numerical values for both energy and mass transfer coefficients, values which have been taken from a variety of sources. Many authors returned to correlations published from experimental work done to predict capacity coefficients as a function of L/G (Leva, 1955), while others developed their own correlations by reviewing published data (Sherwood and Pigford, 1952). Park and Vance (1972), working with a crossflow tower, related KaV/L as:

$$KaV/L = 1.25(L/G)^{-0.75} \,, \qquad 1.3$$

following the Merkel effort. Other authors applied generalized correlations, employing the Chilton-Colburn analogy between mass and energy transfer to convert between coefficients. In the paper previously referred to above, Nahavandi and Oellinger (1977) employed the Chilton-Colburn analogy to convert Gilliland's (Bird et al, 1960) wetted wall equation for an overall mass transfer coefficient in terms of Schmidt and Reynolds number to an expression for an overall heat transfer coefficient using the Prandtl and Reynolds numbers:

$$(h_H De)/k_{th} = 0.023\ Pr^{0.44}\ Re^{0.83} \qquad 1.4$$

Thesis Objectives

Given the widespread use of computers as design tools, the length of time cooling towers have been a part of manufacturing systems, and the relatively simple mechanical and thermodynamic design principles involved, the commonly encountered 100% or more safety factor for cooling towers is surprising. Although the researchers referred to above have spent considerable effort to evaluate the effect of Merkel's assumption on design techniques, no effort has been made to evaluate the assumptions made in standard design approaches and their effects on tower designs, or even to rank them in terms of importance as they contribute to design performance margins. An example of a common assumption is the practice of assuming that the air exiting the unit is saturated, the vapor conditions inside the unit being otherwise ignored (Kelly and Swenson, 1956). Although this assumption does allow the maximum possible evaporation rate to be determined, the mass transfer driving force is reduced to zero, evaporative cooling is eliminated, and the cooling tower functions only as a heat exchanger, drastically reducing its capacity to operate at the design point.

The specific purposes of this work are:

(1) To present a generalized cooling tower computer program which can be used as a teaching program, a design tool, and an analytical or performance based simulation

system;

(2) To present a wide variety of options and features available to the user to explore various aspects of the design and performance analysis process;

(3) To incorporate, investigate, and emphasize the relationship and involvement of the gas stream condition as an integral aspect of the design process, and

(4) To examine several of the variables involved in cooling tower design and examine their role and relative importance as they contribute to determination of an adequate safety factor.

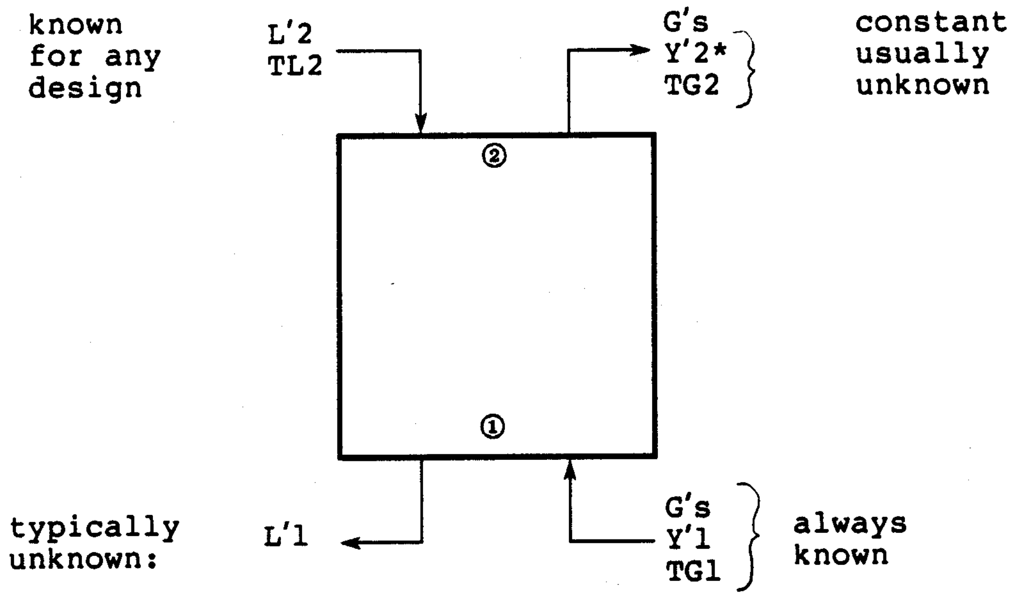
II. MODEL DEVELOPMENT

Design Problem Statement

A representation of a piece of contacting equipment is presented schematically in Figure 4. The equipment itself is shown as a box, and the four streams which indicate the entrance and exit conditions of the gas and liquid phases. Common convention indicates that a subscript 1 is assigned to conditions at the bottom of the unit, and a 2 is used to denote the top of the equipment.

For cooling tower equipment, the mass flowrate L'2 entering the top of the structure is known, as is the temperature, TL2. Since cooling the liquid stream is the principal goal of the design, the exit liquid temperature TL1 is specified, but because of evaporative losses, the exiting liquid mass flowrate L'1 is unknown. Similarly, the entrance conditions of the gas stream (G's, Y'1, and TG1) are known for a geographical site, but both the exit humidity Y'2 and TG2, the exit gas temperature, are not.

In the design of humidification equipment, the exit humidity Y'2 is specified rather than unknown, and TL1 becomes an unknown. In actual practice several of the parameters listed as knowns vary, such as the entering gas temperature, which often undergoes daily variations, so the word "known" means either that an adequate average can



specified: TL1

Variable	Status
G's	Known
Y'2*	Unknown
TG2	Unknown
Y'1	Known
TG1	Known
L'2	Known
TL2	Known
L'1	Unknown
TL1	Known

* specifying Y'2 is a humidification design problem.

Figure 4. Contacting equipment schematic.

be obtained, or that the variable is a primary control variable, such as controlling the liquid flowrate to achieve a target exit gas temperature or humidity. The solution to sizing a piece of contact equipment, therefore, will require equations which will predict changes in temperature and mass flowrate for both streams; the following section describes the derivation of the equations required to solve for the unknowns discussed above.

Fundamental Equation Development

In the following paragraphs, the differential equations used to solve for the unknowns presented in the previous section are discussed. A list of the symbols used in the derivation of the differential equations is given in Appendix A1.

Imagine a cross section through a piece of counterflow exchange equipment, such as the one shown in Figure 4. If we consider the total interfacial area in a column volume of Adz, we would see an arrangement similar to Figure 5. This figure shows three control volumes: (1) the liquid phase, flowing down on the left, (2) the gas phase, rising

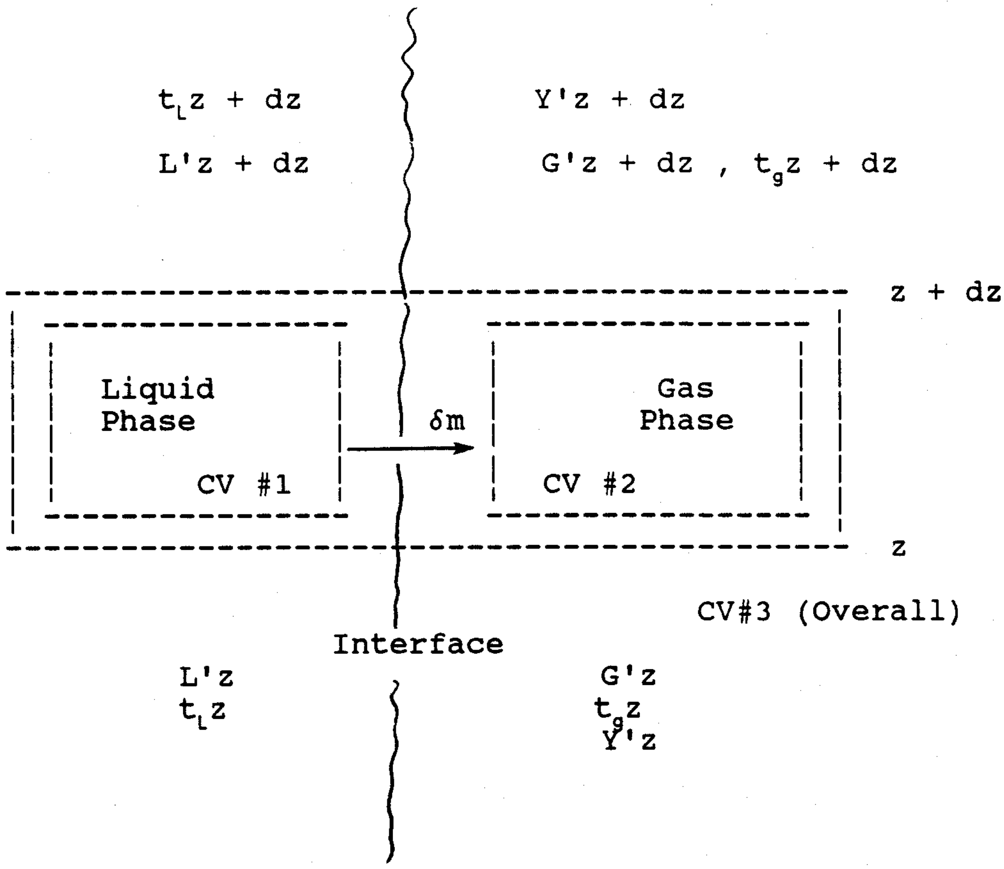


Figure 5. Differential element.

on the right, and (3) an overall control volume encompassing both the liquid and gas phases. The gas-liquid interface is shown as a wavy line, and δm is the element of mass transferring from the liquid (δme) and entering the gas (δmi).

For the sake of the derivation, assume furthermore that we are cooling the liquid stream. Figure 6 presents the thermal profile through our differential element, showing temperature gradients in both phases, as well as the directions for mass, latent, and convective energy transfer.

A. Mass Transfer Equations

For the case in which the liquid is being cooled, mass transfer occurs from liquid to gas, as shown in Figure 5. If we list the inputs and outputs from CV#2, the gas phase, we have:

Inputs $G'sY'z + \delta mi$

Output $G'sY'z + dz$

For the case of steady flow, inputs equal outputs, so:

$$G'sY'z + dz = G'sY'z + \delta mi \qquad 2.1$$

and finally,

$$G'sdY' = \delta mi \qquad 2.2$$

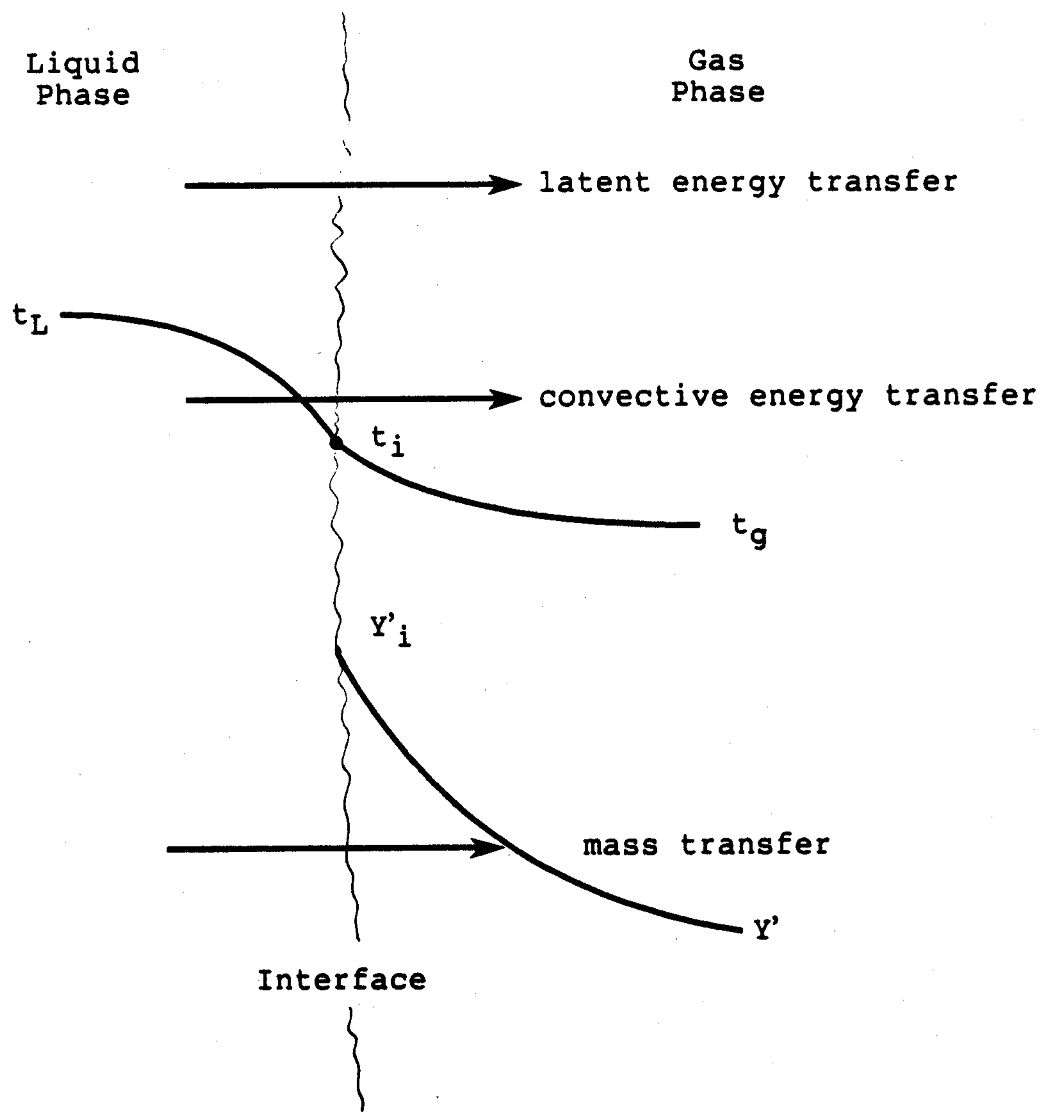


Figure 6. Thermal profile of a differential element.

If we express δmi in terms of a mass transfer equation,

$$G'sdY' = \delta mi = k_{Y'}a_m(Y'_i - Y')dz \qquad 2.3$$

or

$$dY' = \frac{k_{Y'}a_m}{G's}(Y'_i - Y')dz \qquad 2.4$$

A corresponding list of inputs and outputs for CV#1, the liquid phase, yields:

Inputs $\quad L'z + dz$

Outputs $\quad L'z + \delta me$

Once again, inputs equal outputs, so:

$$L'z + dz = L'z + \delta me \qquad 2.5$$

or

$$dL' = \delta me \qquad 2.6$$

Since $\quad \delta me = \delta mi \quad ,$

we can equate 2.2 and 2.6 to obtain:

$$G'sdY' = \delta mi = \delta me = dL' \qquad 2.7$$

B. Energy Transfer Equations

1. Liquid Phase

For CV#1, the liquid phase, there is a single input from the enthalpy of the incoming liquid, but there are three outputs: one from the enthalpy of the exiting liquid, a second from the enthalpy of the mass transferring to the gas stream, and a third term which expresses the convective heat transfer from the bulk liquid to the interface, as shown in Figure 2.

Input $L'z + dz\ Ha_Lz + dz$

Outputs $L'zHa_Lz + meHa_{Li} + h_La_H(t_L-t_i)dz$

Since $\delta me = G'sdY'$ 2.8

and $dHa_L = C_Ldt_L$ 2.9

we equate the inputs and the outputs, substitute for the terms above, and rearrange to yield:

$$L'C_Ldt_L = (t_i-t_L)\ [C_LG'sdY' - h_La_Hdz] \qquad 2.10$$

expressed in terms of the change in the liquid temperature,

$$dt_L = \frac{G'sdY'}{L'}(t_i - t_L) - \frac{h_La_Hdz}{L'C_L}(t_i - t_L) \qquad 2.11$$

2. Gas Phase

Since the liquid phase outputs become gas phase inputs, we have three: the incoming vapor enthalpy, the enthalpy associated with the mass transferring from liquid to gas, and the convection term:

Inputs $G'sH'z + Ha\delta mi + h_ga_H(t_i - t_g)dz$

Output $G'sH'z + dz$

equating input to output,

$$G'sdH' - G'sHadY' + h_ga_H(t_g-t_i)dz = 0 \qquad 2.12$$

since

$$H' = C_S(tg - t_0) + Y\lambda_0 \qquad 2.13$$

and $C_S = Cb + Y'Ca$ 2.14

$$dH' = C_Sdt_g + HadY' , \qquad 2.15$$

which we substitute to obtain

$$dt_g = \frac{h_g a_H}{G'sC_S}(t_i - t_g)\, dz \qquad 2.16$$

C. Differential Equation Summary

Mass Transfer Equations:

$$dY' = \frac{k_{Y'} a_m}{G's}(Y'_i - Y')dz \qquad 2.4$$

$$dL' = G'sdY' \qquad 2.7$$

Energy Transfer Equations:

$$dt_g = \frac{h_g a_H}{G'sC_S}(t_i - t_g)\, dz \qquad 2.16$$

$$dt_L = \frac{G'sdY'}{L'}(t_i - t_L) - \frac{h_L a_H dz}{L'C_L}(t_i - t_L) \qquad 2.11$$

Application To A General Solution

Each of the four differential equations previously derived can be applied to a design problem once they have been integrated. Since we wish to integrate as a function of height, z, all of the variables need to be expressed as a function of height, or assigned an average value if the increment delta-z (Δz) is chosen to be very small. If we treat the variables as constants assigned to an average value within the increment, integrate each of the equations as a function of delta-z , and express the results in difference form, we obtain:

1. Mass Transfer Equations:

$$\Delta Y' = \frac{k_{Y'}a}{G's} (Y'_i - Y')avg\Delta z \qquad 2.17$$

or

$$Y'2 = Y'1 + \Delta Y' \qquad 2.18$$

$$\Delta L' = G's\Delta Y' \qquad 2.19$$

or

$$L'2 = L'1 + \Delta L' \qquad 2.20$$

2. Energy Transfer Equations:

$$\Delta t_g = \frac{h_g a_H}{G'sC_s avg} (t_i - t_g)avg\Delta z \qquad 2.21$$

or

$$TG2 = TG1 + \Delta t_g \qquad 2.22$$

$$\Delta t_L = \frac{G's\Delta Y'}{L'avg} (t_i - t_L)avg - \frac{h_L a_H \Delta z}{L'avgC_L} (t_i - t_L)avg \qquad 2.23$$

or

$$TL2 = TL1 + \Delta t_L \qquad 2.24$$

As equations 2.18, 2.20, 2.22, and 2.24 show, there are four equations involved in the solution to a general design, and so there must be four unknowns. Reference to Figure 4 shows that there are four: Y'2, TG2, L'1, and the tower height of packing, Z. Subsequent sections will develop the methods used to calculate each of the values used in the equations, such as the interfacial temperature, mass transfer coefficients, and heat capacities. If all the variables can be determined, these four differential equations can be applied directly to the solution of a design problem.

Solving A Design Problem

Since some of the conditions at the top and the bottom of the column are unknown initially, the solution to a design problem requires a trial and error approach. Referring to Figure 4, if a value for L'1 is guessed, equations 2.17 through 2.24 can be used to predict the values at the top of a small increment of height delta-z. Once the values at the top of the increment are known, the element can be moved up another increment, and the process repeated stepwise until the conditions at the top of the column are attained. From the conditions at the top of the column an improved guess for L'1 can be made, and another trial may begin. A "correct" solution is achieved when the value of L'1 results in predicting a correct value for both L'2 and TL2, and the size of the piece of equipment is the sum of the increments of height necessary to attain the exit conditions. The following steps outline the process in detail:

1. Set the initial increment at the bottom of the column.

2. From Figure 4, the only value unknown is L'1, which is guessed.

3. The interfacial temperature is calculated, and the terms labelled averages in equations 2.17, 2.19, 2.21, and 2.23 are evaluated based on conditions at the bottom of the

increment.

4. Equations 2.18, 2.20, 2.22, and 2.24 are used to predict conditions at the top of the increment.

5. The values predicted at the top of the increment are used to solve for the interfacial temperature at the top of the increment.

6. The terms labelled averages in Figure 3 are evaluated using the values for the top of the element.

7. An actual set of averages is determined by combining the averages for the bottom and the top of the element.

8. The actual averages are used with the values at the bottom of the column in equations 2.18, 2.20, 2.22, and 2.24 to repredict values at the top of the increment.

9. Step 8 is repeated six times to improve the set of averages and to recalculate the values at the top of the increment.

10. At the end of the sixth iteration, the difference element is incremented by Δz, the values at the top of the previous element are used as the bottom values for the new increment, and the process is repeated until TL2 is attained. The final element interpolates to obtain TL2 exactly.

11. When the final element is reached, the value for L'1 is given, which can be used as a starting guess for a new integration. The process is repeated until the choice of

L'1 correctly predicts both L'2 and TL2.

The following paragraphs discuss in topical form the determination of the additional information required to perform the numerical integration developed in the preceding section.

NTU Integration

As equation 1.2 shows, the capacity coefficient or tower characteristic could be determined by an integration of the right hand side of the expression, which is related to the shaded area in Figure 1. For the derivation presented here, equation 2.35, which is strictly true only for the case of no liquid evaporation, can be expressed in similar form, yielding an similar expression:

$$Z = \frac{G's}{k_{Y'}a} \int_{1}^{2} \frac{(dH')}{(H'_i - H')} \qquad 2.35$$

The integral of this expression, which yields the tower height, is described of two parts: (1) $G's/k_{Y'}a$, also known as the height of a transfer unit, HTG, and (2) the area integral, which is called the number of transfer units, NTU. The shaded area in Figure 1 is related to the NTU integral above. The larger the shaded area, the greater the difference between the interface and bulk gas enthalpies, thus the smaller the height required, since the difference between the enthalpies is in the denominator. Expressed simply, the smaller the shaded area, the greater the amount of fill required.

Since the NTU concept and the associated graphical integration are fundamental to the understanding of cooling tower design, the design program calculates NTU using the trapezoidal rule for each element of tower height, and the result is printed after each run. The value can be compared to the NTU obtained by dividing the tower height by NTG as an estimate of the error caused by neglecting the liquid loss due to evaporation.

Auxiliary Equations

A. Interfacial Conditions

1. Standard Case: t_i not equal to t_L

Since the interface is considered saturated, the interfacial temperature is sufficient to obtain the saturation enthalpy and absolute humidity.

At this point the assumption is made that there is no liquid loss, i.e., dL' = 0. Proceeding from equation derived as a liquid phase energy transfer function, we have:

$$L'C_L dt_L = (t_i - t_L)[C_L G's dY' - h_L a_H dz] \quad 2.25$$

From the mass transfer equation

$$G's dY' = dL' \quad 2.7$$

but since dL' = 0,

$$L'C_L dt_L = h_L a_H \ (t_L - t_i) \ dz \quad 2.26$$

From an overall energy balance around CV#3 we can say that

$$d(L'Ha_L) = G's dH' \quad 2.27$$

and since $dHa_L = C_L dt_L$, and for constant L', 2.9

$$L'C_L dt_L = G's dH' \quad 2.28$$

which we substitute to obtain

$$G's dH' = h_L a_H \ (t_L - t_i) \ dz \quad 2.29$$

In order to develop another equation needed here, we write an energy balance around the interface itself. The single input comes from the convective energy brought from the bulk liquid to the interface, and there are two output terms, one from gas phase convection, the other from the latent heat associated with the mass transfer from liquid to gas.

Input: $h_L a_H \ (t_L - t_i) \ dz$

Outputs: $[k_{Y'} a_m (Y'_i - Y')](Ha - Ha_L) + h_g a_H (t_i - t_g) dz$

If we equate the two expressions, and since from above we have

$$G'sdH' = h_L a_H (t_L - t_i) dz \qquad 2.29$$

we have

$$G'sdH' = [k_{Y'} a_m (Y'_i - Y')](Ha - Ha_L) + h_g a_H (t_i - t_g) \qquad 2.30$$

We now assume (1) that the area available for energy transfer is the same for mass transfer, so that

$$a_m = a_H = a \ , \qquad 2.31$$

and that (2) the Lewis relation holds:

$$h_g = k_{Y'} C_S \qquad 2.32$$

We also expand the enthalpy terms as

$$H'_i = C_S(t_i - t_0) + Y'_i \lambda_0 \qquad 2.33$$

and

$$H' = C_S(t_g - t_0) + Y' \lambda_0 \qquad 2.34$$

substitute the above, and have as a result:

$$G'sdH' = k_{Y'} a (H'_i - H') dz \qquad 2.35$$

If we equate the right hand sides of equations 2.35 and 2.29,

$$k_{Y'}a(H'_i - H') = h_L a(t_L - t_i) \qquad 2.36$$

Since t_i is the desired value, the equation is rearranged to yield

$$t_i = t_L + \frac{H'_i - H'}{(-h_L a/k_{Y'}a)} \qquad 2.37$$

2. Alternate Case: ti equal to t_L

A common assumption in cooling tower design theory is that no liquid thermal gradient exists, which is equivalent to stating that the liquid phase heat transfer coefficient is infinite. In this case equation 2.11, used to predict the temperature change in the liquid phase, becomes indeterminate:

$$dt_L = \frac{C_L G'sdY'}{L'}(t_i - t_L) - \frac{h_L a_H z}{L'C_L}(t_i - t_L) \qquad 2.11$$

In both terms $t_i - t_L$ equals zero, and in the second term since h_L is infinite, infinity is multiplying zero.

From the overall balance written around CV#3 we have already shown that

$$d(L'Ha_L) = G'sdH' \qquad 2.27$$

which, integrated, becomes

$$L'2Ha_L2 - L'1Ha_L1 = G's\,(H'2 - H'1) \qquad 2.38$$

substituting for the enthalpy terms

$$Ha_L = C_L(t_i - t_0) \qquad 2.39$$

$$H' = C_S(t_g - t_0) + Y'\lambda_0, \qquad 2.34$$

we have

$$L'2C_L(TL2 - t_0) - L'1C_L(TL1 - t_0) \qquad 2.40$$

$= G's\{[C_s2(TG2-t_0) + Y'2\lambda_0] - [C_s1(TG1-t_0) + Y'1\lambda_0]\}$

This equation is independent of t_i and can be used to solve for the liquid temperature.

B. Energy And Mass Transfer Coefficients

Given the tremendous variation in heat and mass transfer coefficients encountered in the literature, and because the program was intended to design and simulate both packed columns and cooling towers, a wide variety of mass and energy transfer coefficient calculations have been incorporated. Although the recently proposed Fair (1972) and Bolles and Fair (1982) mass transfer model represents the most contemporary model available, the Shulman (1959) techniques as adapted by Treybal (1980b, pages 203-209) were incorporated into the model because of their ease of adaptability for machine calculations, rather than from the standpoint that they are more accurate than the Fair and Bolles' model. In order to study the variation in transfer coefficients within a piece of equipment, the user has the choice of recalculating the coefficients for each increment or holding them constant after an initial evaluation based on conditions at the bottom of the tower. The Shulman model is available for Rashig rings from 187 mm (1/2 in.) to 364 mm (2 in.) and for Berl saddles from 187 mm (1/2 in.) to 256 mm (1.5 in.). If the user specifies the use of the Shulman model, the program prints two pages of calculations illustrating the application of this model to the design under consideration.

In order to predict mass transfer coefficients for cooling towers, two correlations derived from test towers are included in the program, one developed by J. R. Lichtenstein in 1943, the other by A. S. Norman in 1961. Both correlations are power functions of L' and G' alone, and values are maintained constant after an initial evaluation based upon conditions at the bottom of the column.

The final choice is to enter the mass transfer coefficient directly. The User's Manual, Appendix A2, discusses the techniques for converting related information such as Htg, Htog, or a tower capacity coefficient into $k_{Y'}a$.

Once $k_{Y'}a$ has been determined, the Lewis relation and the Chilton-Colburn analogy are both appropriate to determine $h_g a$, the gas phase heat transfer coefficient. The Lewis relationship, which is true only for the air/water system, requires no information other than the mass transfer coefficients:

$$h_g a / k_{Y'} a = C_S \qquad 2.41$$

The Chilton-Colburn analogy, however, requires the calculation of several gas phase parameters:

$$j_D = j_H = \frac{h_g}{Cp_G} Pr_g^{(2/3)} \qquad 2.42$$

The parameters needed are provided by functions which accept gas phase variables as their arguments. Both values of hga are calculated from which the user may choose.

Unfortunately, the calculation of $h_L a$, the liquid phase transfer coefficient, is not as simple. Since the liquid is pure water, the liquid phase mass transfer coefficient does not exist, and there are no correlations available to predict liquid heat transfer coefficients for cooling towers. The Shulman model can be used to predict a liquid phase heat transfer coefficient, and although the coefficient is hypothetical, the technique does provide a means of determining hla for design purposes.

The program also allows $h_L a$ to be calculated by analogy to the packed column model. Using the data for a particular design, $h_L a$ and $h_g a$ are determined by the Shulman model. Although the magnitude of the gas and liquid heat transfer coefficients is quite different for the two types of equipment, a more realistic assumption is that the ratio of $h_L a$ to $h_g a$ is similar in both cases. Therefore, $h_L a$ for a cooling tower can be approximated by the following equation:

$$h_L a\text{, cooling tower} = h_g a\text{, cooling tower} * (h_L a/h_g a)\text{Shulman} \qquad 2.43$$

This equation is used to predict $h_L a$ from $h_g a$-Lewis as well as from $h_g a$-Chilton-Colburn. The user may accept either value of both $h_g a$ and $h_L a$, or may enter any value desired.

C. Other Program Data

The following paragraphs describe the techniques used to obtain the additional information needed in the program. The functions and constants used here agree with standard thermodynamic practice. The topics are presented in the same order which they appear in the program listing summary, appendix A3.3.

Appendix A3 provides a detailed description of the computer program developed from the model discussed in the previous section. Included in the section is a discussion of the techniques used to convert the differential equations into code, program flow, subroutine development, and other program details.

1. Interfacial Conditions

Figure 7 illustrates the determination of the interfacial conditions. At an arbitrary location in the column, the liquid temperature is plotted at the enthalpy of the gas stream on an enthalpy-temperature diagram, point number 1. Since the interface is assumed to be saturated at the interfacial temperature, a tie line can be constructed from point #1 to the saturation enthalpy line, the slope of which is $-h_L a/k_{Y'} a$. The interfacial temperature is read at the intersection of the tie line and the saturation enthalpy curve. Numerically, the procedure is:

1. The point-slope formula for a straight line is:

$$Y2 - Y1 = M\ (X2 - X1)$$

In the desired coordinates, this becomes

$$H'_i - H' = (-h_L a/k_{Y'} a) * (t_i - t_L)$$

Since t_i is the desired value, the equation is rearranged to yield:

$$t_i = t_L + (H'_i - H') / (-h_L a/k_{Y'} a)$$

2. As a starting value, evaluate H'_i at t_L. Use this value to predict t_i.
3. Use the predicted value of t_i to recalculate H'_i.
4. Use the value of H'_i to recalculate t_i.
5. Repeat #3 and #4 until the new value of t_i agrees with the previous value within 0.05 degrees.

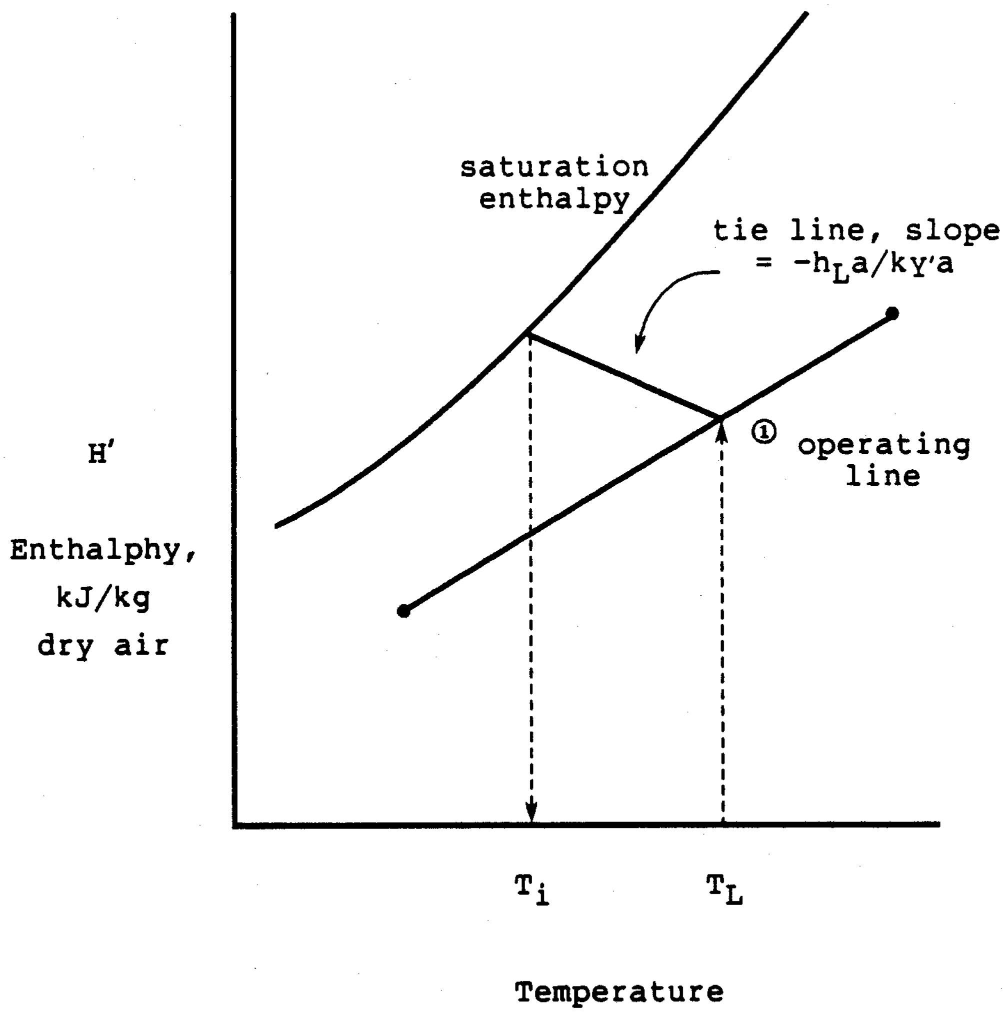


Figure 7. Interfacial temperature determination.

2. Prandtl Number

The dimensionless Prandtl number is defined as:

$Pr = Cp(T) * \mu(T) / k_{th} (T)$

For the gas phase, the film temperature is used in calculating all three parameters; for the liquid, the viscosity and thermal conductivity are calculated from the liquid temperature, while the heat capacity is a constant, 4178 N-m/kg-K.

3. Gas Phase Heat Capacity

The gas phase heat capacity is calculated from an equation published in the <u>Thermodynamic Properties Of Air</u> (Goff, 1983):

$$Cp = [a + b(T) + c(T)^2 + d(T)^3]\ 1000/28.97 \quad \text{N-m/kg-K}$$

where

$a = 28.09$

$b = 1.965E-03$

$c = 4.799E-06$

$d = -1.965E-09$

T = the film temperature, degrees K

4. Bulk Gas Enthalpy

The bulk gas enthalpy is calculated from the following equation:

$$H' = C_s(T, Y')*T + (Y' * 2502300) \qquad J/kg\ air$$

5. Gas Phase Schmidt Number

The dimensionless gas phase Schmidt number is used in the Schulman model, and is defined by the following equation:

$$Sc_g = \mu_g(T) / (\rho_g(T) * D_{ab}(T))$$

where T refers to the film temperature.

6. Gas Phase Diffusivity

The diffusivity of water vapor in air at 298.15K is given as:

$D_{ab} = 2.634 / P \quad m^2\text{-}Pa/sec$, where P = 1 atm = 101,325 Pa.

The value of D_{ab} is corrected for the effects of temperature by the Hirshfelder equation, neglecting the effects of the collision integral, as described in Welty, Wicks, and Wilson, (1976):

$$D_{ab}, T2 = D_{ab}, T1 * (T1/T2)^{(3/2)} \quad m^2/sec$$

7. Gas Phase Density

Since the model treats pressure as constant at one atmosphere, the density of the gas is given by:

$\rho 2 = \rho 1 * T1 / T2 = 353.41 / T$ kg/m^3, where T is taken as the film temperature.

8. Gas Phase Viscosity

The gas phase viscosity is also taken from the Thermodynamics Properties Of Air (Goff, 1983):

$\mu(g) = 1.458E-06 * T^{(3/2)} / T + 110.4$ kg/m-sec

9. Gas Phase Conductivity

The gas phase conductivity is also taken from the Thermodynamic Properties Of Air (Goff, 1983):

$$k_{th}(g) = \frac{1.972577346E-03 * (T)^{(1/2)}}{1.0 + (441.7/T)*(10^{(-21.6/T)})} \quad \text{W/m-K}$$

Where T = film temperature

10. Liquid Phase Viscosity and Conductivity

The liquid phase viscosity and conductivity formulas used in the program were both developed from curve fits from actual data. In final form:

$\mu_L = 1 / [a*(T + b)^2 + c]$ kg/m-sec where: $a = 0.09154996458$

$b = -159.9864214$

$c = -624.090532$

Similarly:

$$k_{th}(L) = a + b/T + (c/T^2) \quad W/m\text{-}K$$

where $a = 0.4955670305$

$b = 207.9173286$

$c = -51654.23419$

T = the film temperature

11. Humid Heat

The humid heat is defined for water vapor in air as:

$C_s = Cp_g(T) + Y'*1884$, J/kg air - C, where 1884 represents the heat capacity of the water as vapor. T is taken as the film temperature.

12. Saturated Absolute Humidity

The saturated absolute humidity is defined as:

$$Y's = \frac{YsMa}{Mb} = \frac{p_a^*}{(p_T - p_a^*)}(Ma/Mb) = \frac{p_a^* * 18.015}{(p_T - p_a^*)*28.95}$$

The saturation vapor pressure, p^*, is calculated in the program from an equation given in the 1968 ASME Steam Tables (Mc Clintock and Silvestri, 1968):

$$p_a^* = \frac{22,120,000 * 0.0254 * 0.0254}{9.80665 * 0.45359237} * \beta_k$$

where β_k is defined as:

$$\beta_k(\theta) =$$

$$\exp\left\{\frac{1}{\theta}\left[\frac{\sum_{\nu=1}^{5} k_\nu (1-\theta) ** \nu}{[1 + k6(1-\theta) + k7(1-\theta)^2]} - \frac{1-\theta}{k8(1-\theta)^2 + k9}\right]\right\}$$

where θ is defined as the reduced temperature, with Tc = 647.3K for water, and:

k1 = -7.691234564

k2 = -26.08023696

k3 = -168.1706546

k4 = 64.23285504

k5 = -118.9646225

k6 = 4.167117320

k7 = 20.97506760

k8 = 10^9

k9 = 6.00

III. MODEL VALIDATION, APPLICATIONS, AND EXTENSIONS

This section discusses the working model, both from software as well as application perspectives, then goes on to show a few possible extensions, in particular how to use the model to obtain mass transfer coefficients from performance data. The majority of the analysis is found in the Applications section, particularly the mechanical draft tower example, in which the major parameters of the model are developed in detail. Shorter examples of natural draft and packed column designs are also given.

Details of running the program are given in the User's Manual, Appendix A2. Since the primary goal of developing the model was to create an interactive teaching program for undergraduate students, many options are given in the software which are not discussed at length in the body of the text. Each of the options is covered in the User's Manual, but is not discussed in each of the applications. The user is free to experiment with as many as may be desired; each example lists which options were chosen for each run.

Validation Of The Model

The program was written in modular form, then assembled into larger units. Dimensional analysis was used on each of the functions and subroutines, and dummy print statements were added to the early program test runs for comparison with hand calculations. Once the program was finalized, hand calculations were performed on each option. Finally, the model was tested on classroom, textbook, and published examples; in each case, graphical analysis was used to compare with the program output to validate the model. To the extent that the assumptions used in the example matched those in the model, no errors were found.

The approach used to solve the four differential equations has already discussed; in general, an iterative (Eulerian) approach was used. This technique was chosen because the point of the model was to automate hand calculations as taught to undergraduate students, and to study the effect of various options on their solutions to a design problem.

Although frequently used in the solution of differential equations, the Eulerian approach suffers from very low accuracy, and does not result in convergence for unstable equations. In all cases tested in this study, the equations were stable and converged easily. During the program development stage, the number of iterations needed was studied in detail; error functions were built into the model, and the program was required to iterate until a user-specified level of accuracy was attained. The greatest number of iterations are needed at the bottom of the tower; as the program moves up the tower the driving force diminishes, and the number of iterations needed for the same degree of accuracy within an element was reduced. The final value of six iterations per element was chosen and incorporated into the model. This number provided solutions to all the examples studied which showed no effect of the number of iterations used.

Applications To Standard Designs

None of the published reports on existing towers or their design provided all the details necessary to develop an exact parallel to the model developed here, but a few examples were sufficiently detailed to provide a basis for comparison. Each of the examples presented below is used to demonstrate a particular aspect of the design program, and the discussions include any assumptions made in order to use the example. Details for each of the examples are given in the Appendices.

The first example, the mechanical draft cooling tower, was arbitrarily chosen to be the most fully analyzed; many of the points studied in this case are not repeated in subsequent examples. Both natural draft as well as packed column examples are also included.

A. Mechanical Draft Towers

The following discussion is based on the design of a series of cooling towers for the 30 megawatt nuclear power plant in Paducah, Kentucky, reviewed by R. B. Wrinkle in his 1974 article "The Design Of Natural Draft Cooling Towers" (Wrinkle, 1972). In contrast to most journal articles, this article provided all but one piece of data to simulate the design of the system; the entering air humidity had to be estimated from the geographical data provided in Table 25, Appendix A2. The process information used in the example and the design output is summarized in Table 1, and details of running the Paducah example are given in the user's manual, Appendix A2. The model output from these data is found in Figure 8.

The Paducah design article also did not mention either the technique used for the design, or the choice of safety factors, margins, or worst cases taken into account in the design; this makes a comparison of the absolute accuracy of the model to any example nearly impossible. In place of this, the effect of each parameter on the model is discussed.

The tower height given in the article is 49 feet, or 14.9 meters; using parameters taken from the article yielded a design height of 12.0 meters, which agrees with the article within 20%. If the entrance humidity value is raised slightly, the exact height of the example can be obtained; varying other parameters slightly will also provide the same result. The point was not to obtain the "right" answer, but to study the affect of parameter selection on the design. The article also does not state explicitly that the packed height is 49 feet; the affect of risers, spray nozzles, demisters, fans, and catch basins would be expected to reduce the height of the packed area.

Table 1. Mechanical draft cooling tower input and design summary.

Inputs:

TL2 = 61.43 deg. C
TL1 = 32.21 deg. C
TG1 = 36.0 deg. C
L'2 = 2.19 kg/m2-sec
G'1 = 5.475 kg/m2-sec
Y'1 = 0.0182
L/G = 0.4
Delta-Z = 0.25m
$k_{Y'}a$ = 0.252 kg/m^3-sec
$T_i = T_L$
Chilton Colburn mass transfer option, constant

Outputs:

Packed height, meters 12.0

L'1 = 2.087

Exit gas relative humidity 83.2%

Number of iterations required
for 2 place accuracy of L'1 2

NTG = 0.5619

```
                    PACKED COLUMN/COOLING TOWER DESIGN

                          INTEGRATION NUMBER  1

MECHANICAL DRAFT COOLING TOWER EXAMPLE

TL2 =  61.43                   TG2  unknown          VARIABLE      UNITS
L'2 =   2.190   ====>X  X====>  Y'2  unknown          -----------------------
                     X  X                             TEMPERATURES  DEGREES C
                     X  X                             FLOW RATES    kg/m2-sec
                  XXXXXXXXXX
        Z PLUS    X   2.   X
      DELTA Z ----X--------X----
                  X        X    DELTA Z =  .250 meters
            Z ----X--------X----
                  X        X                          DESIGN PARAMETERS
                  X   1.   X                          ---------------------------------------------
                  XXXXXXXXXX
                     X  X                             CRITICAL RELATIVE HUMIDITY  =  100.0
TL1 =  32.21         X  X      TG1  =  36.00          L/G RATIO =   .40
L'1   unknown   <====X  X<==== Y'1  =    .0182
                               G'1  =  5.475
                               G'S  =  5.377
```

GAS STREAM MASS TRANSFER			PROCESS ENERGY AND MASS DATA			TEMPERATURES IN DEGREES CENTIGRADE				HEAT AND MASS TRANSFER COEFFICIENTS		
SATURATION HUMIDITY (kg/kg)	BULK GAS HUMIDITY (kg/kg)	RELATIVE HUMIDITY (%)	BULK GAS ENTHALPY (kJ/kg)	LIQUID RATE (kg/m2s)	GAS RATE (kg/m2s)	LIQUID (C)	INTERFACE (C)	BULK GAS (C)	HEIGHT (m)	GAS hga (W/m3sK)	LIQUID hla (W/m3sK)	MASS kYa (kg/m3s)
.030992	.018200	48.5	82.9	2.0870	5.4750	32.21	32.21	36.00	.000	230.6	9263.1	.25200
.031366	.018351	49.0	83.3	2.0878	5.4742	32.41	32.41	35.96	.250	230.6	9263.1	.25200
.031754	.018505	49.5	83.6	2.0886	5.4750	32.62	32.62	35.93	.500	230.6	9263.1	.25200
.032158	.018662	50.0	84.0	2.0895	5.4758	32.83	32.83	35.89	.750	230.6	9263.1	.25200
.032578	.018821	50.5	84.4	2.0903	5.4766	33.05	33.05	35.86	1.000	230.6	9263.1	.25200
.033015	.018984	51.0	84.8	2.0912	5.4775	33.28	33.28	35.84	1.250	230.6	9263.1	.25200
.033470	.019150	51.5	85.2	2.0921	5.4783	33.51	33.51	35.81	1.500	230.6	9263.1	.25200
.033945	.019320	52.0	85.6	2.0930	5.4792	33.75	33.75	35.79	1.750	230.6	9263.1	.25200
.034440	.019493	52.5	86.0	2.0940	5.4801	34.00	34.00	35.77	2.000	230.6	9263.1	.25200
.034956	.019670	53.0	86.5	2.0949	5.4810	34.25	34.25	35.75	2.250	230.6	9263.1	.25200
.035496	.019851	53.5	86.9	2.0959	5.4819	34.51	34.51	35.74	2.500	230.6	9263.1	.25200
.036060	.020037	54.0	87.4	2.0969	5.4829	34.78	34.78	35.73	2.750	230.6	9263.1	.25200
.036651	.020227	54.6	87.9	2.0979	5.4839	35.06	35.06	35.72	3.000	230.6	9263.1	.25200
.037269	.020422	55.1	88.3	2.0989	5.4849	35.34	35.34	35.71	3.250	230.6	9263.1	.25200
.037918	.020622	55.6	88.9	2.1000	5.4859	35.64	35.64	35.71	3.500	230.6	9263.1	.25200
.038600	.020827	56.1	89.4	2.1011	5.4869	35.94	35.94	35.71	3.750	230.6	9263.1	.25200
.039316	.021038	56.7	89.9	2.1023	5.4880	36.26	36.26	35.72	4.000	230.6	9263.1	.25200
.040069	.021256	57.2	90.5	2.1034	5.4891	36.59	36.59	35.72	4.250	230.6	9263.1	.25200
.040863	.021480	57.8	91.1	2.1046	5.4902	36.92	36.92	35.73	4.500	230.6	9263.1	.25200
.041701	.021710	58.3	91.7	2.1059	5.4914	37.27	37.27	35.75	4.750	230.6	9263.1	.25200
.042586	.021948	58.9	92.3	2.1072	5.4926	37.63	37.63	35.77	5.000	230.6	9263.1	.25200
.043522	.022194	59.5	93.0	2.1085	5.4938	38.01	38.01	35.79	5.250	230.6	9263.1	.25200
.044514	.022448	60.0	93.7	2.1098	5.4951	38.40	38.40	35.81	5.500	230.6	9263.1	.25200
.045567	.022711	60.6	94.4	2.1113	5.4964	38.80	38.80	35.84	5.750	230.6	9263.1	.25200
.046686	.022984	61.2	95.1	2.1127	5.4978	39.23	39.23	35.87	6.000	230.6	9263.1	.25200
.047879	.023267	61.8	95.9	2.1142	5.4992	39.66	39.66	35.91	6.250	230.6	9263.1	.25200
.049151	.023561	62.4	96.7	2.1158	5.5007	40.12	40.12	35.95	6.500	230.6	9263.1	.25200

Figure 8. Mechanical draft cooling tower design output.

.051971	.024186	63.7	98.4	2.1192	5.5038	41.09	41.09	36.04	7.000	230.6	9263.1	.25200
.053538	.024519	64.3	99.3	2.1210	5.5054	41.61	41.61	36.10	7.250	230.6	9263.1	.25200
.055227	.024867	65.0	100.2	2.1228	5.5071	42.15	42.15	36.16	7.500	230.6	9263.1	.25200
.057051	.025231	65.7	101.2	2.1248	5.5089	42.72	42.72	36.22	7.750	230.6	9263.1	.25200
.059028	.025613	66.4	102.3	2.1269	5.5108	43.32	43.32	36.29	8.000	230.6	9263.1	.25200
.061177	.026015	67.1	103.4	2.1290	5.5127	43.95	43.95	36.36	8.250	230.6	9263.1	.25200
.063522	.026438	67.9	104.6	2.1313	5.5147	44.61	44.61	36.44	8.500	230.6	9263.1	.25200
.066091	.026885	68.7	105.8	2.1337	5.5169	45.31	45.31	36.53	8.750	230.6	9263.1	.25200
.068916	.027358	69.5	107.1	2.1362	5.5192	46.05	46.05	36.62	9.000	230.6	9263.1	.25200
.072040	.027860	70.3	108.5	2.1389	5.5215	46.83	46.83	36.72	9.250	230.6	9263.1	.25200
.075511	.028395	71.2	110.0	2.1418	5.5241	47.66	47.66	36.83	9.500	230.6	9263.1	.25200
.079392	.028967	72.1	111.6	2.1449	5.5267	48.54	48.54	36.94	9.750	230.6	9263.1	.25200
.083759	.029579	73.1	113.3	2.1482	5.5296	49.49	49.49	37.06	10.000	230.6	9263.1	.25200
.088711	.030239	74.1	115.1	2.1517	5.5326	50.51	50.51	37.19	10.250	230.6	9263.1	.25200
.094377	.030953	75.2	117.1	2.1556	5.5359	51.60	51.60	37.33	10.500	230.6	9263.1	.25200
.100923	.031730	76.4	119.3	2.1598	5.5394	52.79	52.79	37.48	10.750	230.6	9263.1	.25200
.108576	.032581	77.6	121.7	2.1643	5.5432	54.08	54.08	37.64	11.000	230.6	9263.1	.25200
.117650	.033519	79.0	124.3	2.1694	5.5473	55.50	55.50	37.81	11.250	230.6	9263.1	.25200
.128593	.034563	80.5	127.1	2.1750	5.5518	57.06	57.06	38.00	11.500	230.6	9263.1	.25200
.142070	.035736	82.2	130.4	2.1813	5.5567	58.80	58.80	38.19	11.750	230.6	9263.1	.25200
.159115	.037074	84.2	134.0	2.1885	5.5621	60.77	60.77	38.41	12.000	230.6	9263.1	.25200
.165283	.037526	84.8	135.3	2.1909	5.5741	61.43	61.43	38.48	12.073	230.6	9263.1	.25200

```
INTEGRATION NUMBER  1 COMPLETE

     MASS BALANCE:  L'2 - L'1 = G's*(Y'2 - Y'1)
     ---- -------

              LIQUID LOSS =   .10392 kg/m2-sec

              VAPOR GAIN  =   .10392 kg/m2-sec

     ENERGY BALANCE:  L'2*Hal2 - L'1*Hal1 = G's*(H'2 - H'1)
     ------ -------

       ENERGY LOST BY LIQUID =     281.4539 kJ/m2-sec

       ENERGY GAINED BY GAS  =     281.4693 kJ/m2-sec

       PERCENT DIFFERENCE BASED ON LIQUID  =    .0 %

       NEW L PRIME 1 = 2.0860841         DIF =   .00091593

       NTG =   .5624
```

Figure 8, continued.

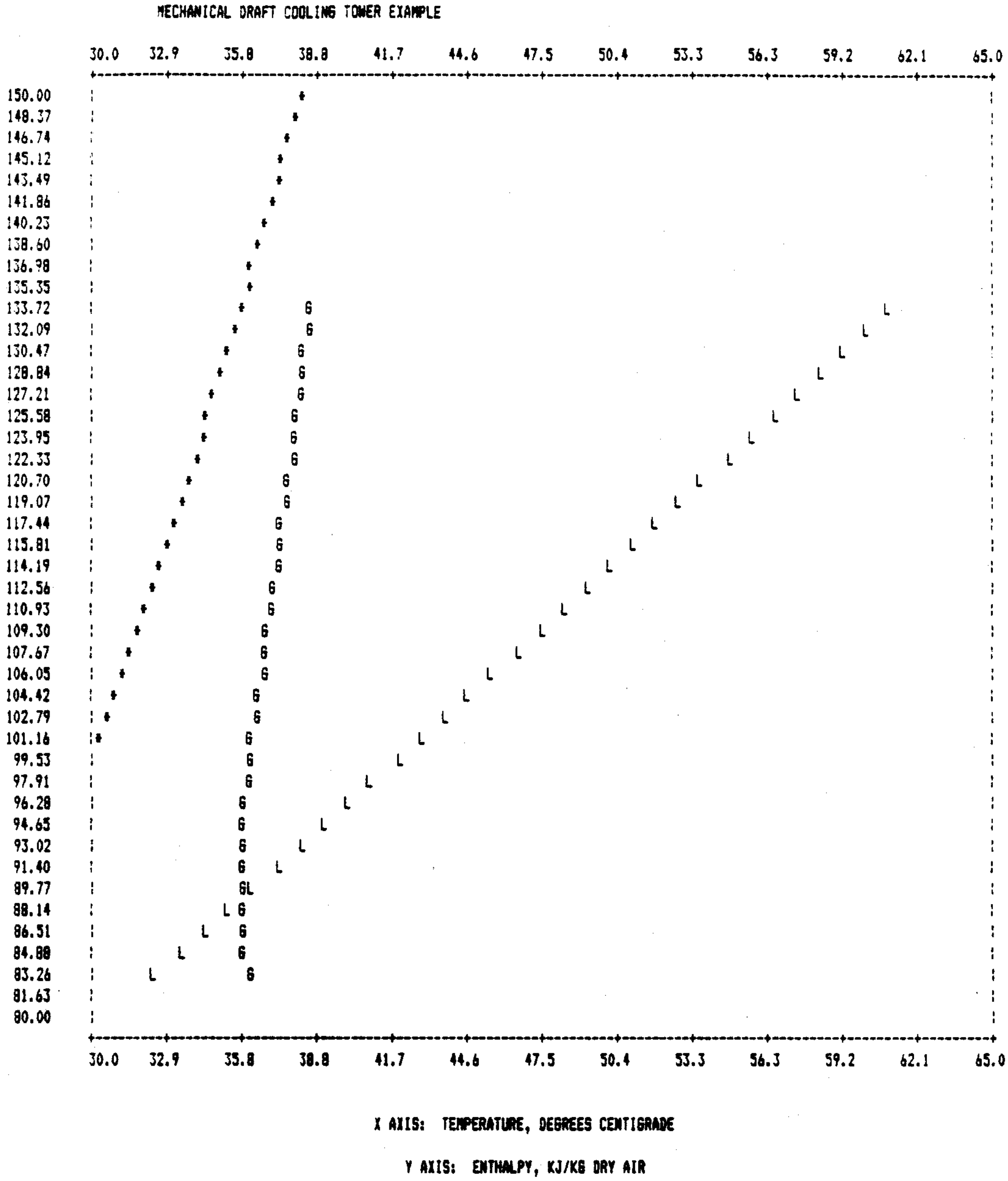


Figure 8, continued.

When the interfacial temperature is set equal to the liquid temperature, two tries were required to bring the design to two place accuracy in terms of both temperature and liquid flows; three tries were required when the interfacial temperature was calculated over each increment. In both cases the 0.1% evaporation loss per degree Fahrenheit of range approach worked well as a starting value for the liquid flowrate exiting the column, L'1 (Hamilton, 1977); the actual evaporation rate, 4.7%, corresponds to 0.1278% per degree Fahrenheit, slightly higher than the original estimate.

Based on an estimated entering air relative humidity of 48.5%, the overall tower height both for the case of $T_i=T_L$ as well as when T_i is calculated agree with the actual height within 10%. Table 2 summarizes the effect of interfacial temperature on the height of fill required. The greater height resulting from T_i being calculated rather than being set equal to T_L is in accordance with the difference between the two models; the case of the interfacial temperature being set equal to the liquid temperature is equivalent to having an infinite liquid phase heat transfer coefficient, requiring less packing to achieve the exit conditions.

The effect of Delta-Z on the design was negligible for increments of height less than 0.2 meters (10 inches); Nahavandi and Oelinger (1977) suggest step sizes less than

Table 2. Effect of interfacial temperature on fill height.

Note: When the interface temperature is calculated, the liquid phase heat transfer coefficient, h_La, is used. The case of $T_i = T_L$ corresponds to an infinite value of h_La. See Figure 7 for a graphical explanation of this relationship.

hLa (W/m^3sK)	Height of fill (m)
10,515	13.4 (Paducah example)
20,000	12.5
50,000	11.7
250,000	11.3
Infinite ($T_i = T_L$)	12.0

1/50th of the estimated packed column height, corresponding to an increment height of 0.24m in this case.

The exit humidity of 83% differs significantly from the standard design assumption that the air/vapor mixture is saturated exiting the tower. If the first estimate of the evaporation rate had been based on the exit conditions being saturated, the first guess for L'1 would have been 27% lower, requiring two more iterations to achieve the same degree of accuracy.

The major inputs to the program were varied to understand their relative contributions to the height of fill required. Figure 9 shows the results of the parameter analysis -- each of the parameters used in the model was varied, and the normalized results of the variation is presented on the X axis. A value of 1.2 corresponds to a 20% increase in the parameter over the value in Table T1, each of which are given the value of 1.0. The Y axis shows the height of fill required for the given set of parameters.

Of the parameters studied, the mass transfer coefficient, the entering gas humidity, and the flow rates contributed most to the height of fill required; the entering liquid temperature and the heat transfer coefficients played relatively minor roles. The increment of height chosen for the model had almost no effect, a result found to be true in all cases studied. A model free of error from the solution technique is convenient;

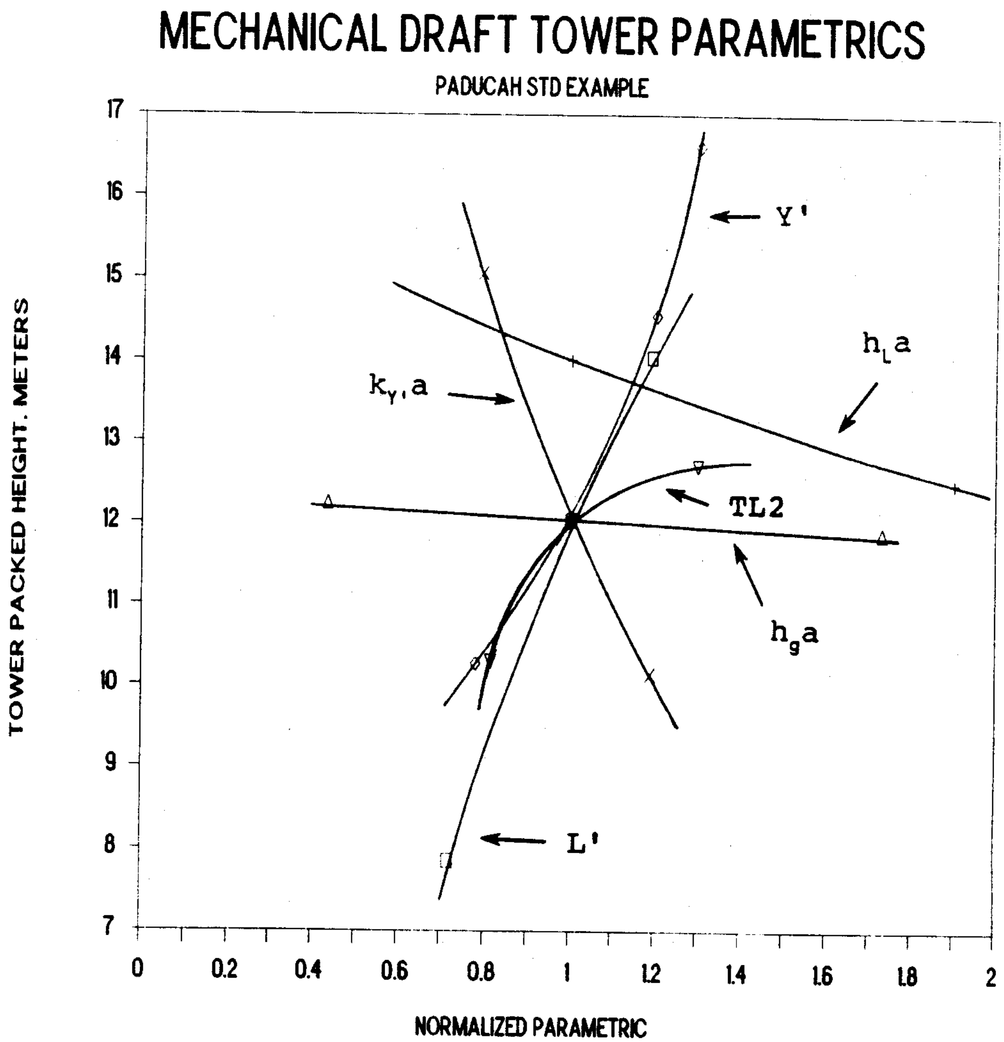


Figure 9. Parameter analysis.

conclusions can be made from the components chosen by the user without complications and interactions from the numerical methods employed.

Explanation of these results is best found with reference two Figure 1 and equation 2.35, as shown in integral form. This equation shows that for a given G's and mass transfer coefficient $k_{Y'}a$, the height of the tower is determined by an area integral which has in the denominator the enthalpy difference between the conditions in the bulk gas stream and those at the interface. At the bottom of the tower, this difference is given by the distance from B to C, which becomes smaller moving from TL1 to TL2 as the conditions in the gas stream approach saturation. The greater the distance between B and C, the smaller the value of 1/(B-C), which is the integral in equation 2.35, and the shorter the height of fill required. The entering gas humidity has a large effect since it largely determines the location of point C relative to the saturation curve. L' also has a direct effect since for a given gas flow G's it determines the operating line CD, again directly affecting the size of the area integral. The mass transfer coefficient directly accounts for the amount of evaporation, and since the energy needed to evaporate comes from the liquid stream, its effect is expected to be quite large -- indeed, this is the real principle of cooling towers.

In a similar manner, the relatively unimportant roles of $h_L a$ and $h_g a$ are easily explained. $H_L a$ only has meaning if the interface temperature is assumed not to be equal to the bulk liquid temperature; this has the effect of giving the chord BC a finite negative slope, since the slope of the chord is the ratio of the heat to the mass transfer coefficients; for all cases found, empirical data show this to be a very large ratio; the heat transfer coefficients are many orders of magnitude greater than mass transfer coefficients. $H_g a$ is also not critical since it accounts for thermal gradients in the gas phase, and since gas phase energy transfer is minuscule compared with the energy transfer due to evaporation, its role is very minor.

B. Natural Draft Towers

The major differences between mechanical and natural draft cooling towers are those imposed by the constraints of convection itself, primarily the low air velocity through the tower. Compared with mechanical draft towers, the heights of fill are very short, the cooling occurring within just a few feet. The vast majority of the tower height which attracts the attention of the public is used to create the natural draft. Although pressure differentials and their associated loss of gas velocities are critical parameters in natural draft designs, they are not treated here. Mass transfer coefficients are similar to those for mechanical draft towers except for the cases of splash fills with large spacing; this is again a consequence of the need for open packing arrangements to avoid loss of air flow. Concrete and redwood splash fills are still common in natural draft towers, both for their low price as well as for their open designs, although their use does result in a lower mass transfer coefficient.

The example given for natural draft cooling towers comes from an article by R. F. Rish, "Design and selection of hyperbolic cooling towers" (Rish and Steel, 1959), which provided performance data from two natural draft towers in England. In this example the model could only simulate the performance information since the design parameters for both towers were not given. Input parameters and design results are summarized in Table 3; Figures 10 presents the design output.

Performance data from this tower were taken from summer processing, thus the exit humidity of 94.3% is not unexpected, since summer presents the worst case approach for entering gas temperature and humidity. The height of fill as designed by the program agrees quite well with the published height of 1.067 meters (3ft. 6 in.).

Table 3. Natural draft cooling tower input and design summary.

Inputs:

TL2 = 31.5 deg. C
TL1 = 22.4 deg. C
TG1 = 11.5 deg. C
L'2 = 1.843 kg/m^2-sec
G'1 = 3.686 kg/m^2-sec
Y'1 = 0.0048
Delta-Z = 0.05 m
$k_{Y'}a$ = 1.37 kg/m^3-sec
$T_i = T_L$
Chilton Colburn mass transfer option, constant

Outputs:

Packed height, meters 1.067

L'1 = 1.8212 kg/m^2-sec

Exit gas relative humidity 94.3%

Number of iterations required
for 2 place accuracy of L'1 2

NTG = 0.3833

```
                    PACKED COLUMN/COOLING TOWER DESIGN

                         INTEGRATION NUMBER  1

STANDARD LEICESTER ENGLAND EXAMPLE

        TL2 =  31.50                TG2  unknown       VARIABLE      UNITS
        L'2 =   1.843   ====>X  X====>  Y'2  unknown       ----------------------
                             X  X                          TEMPERATURES  DEGREES C
                             X  X                          FLOW RATES    kg/m2-sec
                           XXXXXXXXXX
                  Z PLUS   X   2.   X
                 DELTA Z ----X--------X----
                           X        X    DELTA Z =  .050 meters
                     Z ----X--------X----
                           X        X                  DESIGN PARAMETERS
                           X   1.   X                  ------------------------------------------
                           XXXXXXXXXX
                             X  X                      CRITICAL RELATIVE HUMIDITY  =  100.0
        TL1 =  22.40         X  X     TG1  =  11.50    L/G RATIO =   .50
        L'1   unknown   <====X  X<====  Y'1  =    .0048
                                      G'1  =  3.686
                                      G'S  =  3.668
```

GAS STREAM MASS TRANSFER			PROCESS ENERGY AND MASS DATA			TEMPERATURES IN DEGREES CENTIGRADE				HEAT AND MASS TRANSFER COEFFICIENTS		
SATURATION HUMIDITY (kg/kg)	BULK GAS HUMIDITY (kg/kg)	RELATIVE HUMIDITY (%)	BULK GAS ENTHALPY (kJ/kg)	LIQUID RATE (kg/m2s)	GAS RATE (kg/m2s)	LIQUID (C)	INTERFACE (C)	BULK GAS (C)	HEIGHT (m)	GAS hga (W/m3sK)	LIQUID hla (W/m3sK)	MASS kYa (kg/m3s)
.017071	.004800	57.2	23.6	1.8212	3.6860	22.40	22.40	11.50	.000	1223.9	60703.0	1.37000
.017458	.005031	59.2	24.4	1.8220	3.6852	22.76	22.76	11.68	.050	1223.9	60703.0	1.37000
.017857	.005264	61.2	25.2	1.8229	3.6860	23.12	23.12	11.87	.100	1223.9	60703.0	1.37000
.018270	.005501	63.2	26.0	1.8238	3.6868	23.49	23.49	12.05	.150	1223.9	60703.0	1.37000
.018698	.005741	65.1	26.8	1.8247	3.6877	23.86	23.86	12.24	.200	1223.9	60703.0	1.37000
.019141	.005985	67.0	27.6	1.8255	3.6886	24.24	24.24	12.44	.250	1223.9	60703.0	1.37000
.019600	.006233	68.8	28.4	1.8265	3.6894	24.63	24.63	12.63	.300	1223.9	60703.0	1.37000
.020077	.006484	70.6	29.2	1.8274	3.6903	25.02	25.02	12.83	.350	1223.9	60703.0	1.37000
.020572	.006740	72.4	30.1	1.8283	3.6912	25.41	25.41	13.03	.400	1223.9	60703.0	1.37000
.021086	.007001	74.2	30.9	1.8293	3.6922	25.82	25.82	13.24	.450	1223.9	60703.0	1.37000
.021622	.007267	75.9	31.8	1.8302	3.6931	26.23	26.23	13.45	.500	1223.9	60703.0	1.37000
.022179	.007537	77.7	32.7	1.8312	3.6941	26.64	26.64	13.66	.550	1223.9	60703.0	1.37000
.022761	.007814	79.3	33.6	1.8323	3.6950	27.07	27.07	13.87	.600	1223.9	60703.0	1.37000
.023367	.008096	81.0	34.6	1.8333	3.6960	27.50	27.50	14.09	.650	1223.9	60703.0	1.37000
.024001	.008384	82.7	35.5	1.8343	3.6970	27.94	27.94	14.31	.700	1223.9	60703.0	1.37000
.024663	.008679	84.3	36.5	1.8354	3.6981	28.39	28.39	14.54	.750	1223.9	60703.0	1.37000
.025357	.008981	85.9	37.5	1.8365	3.6991	28.85	28.85	14.77	.800	1223.9	60703.0	1.37000
.026085	.009291	87.5	38.5	1.8377	3.7002	29.32	29.32	15.00	.850	1223.9	60703.0	1.37000
.026848	.009609	89.1	39.6	1.8388	3.7013	29.80	29.80	15.24	.900	1223.9	60703.0	1.37000
.027651	.009935	90.7	40.6	1.8400	3.7024	30.29	30.29	15.48	.950	1223.9	60703.0	1.37000
.028497	.010271	92.2	41.7	1.8413	3.7036	30.80	30.80	15.72	1.000	1223.9	60703.0	1.37000
.029388	.010616	93.8	42.9	1.8425	3.7048	31.32	31.32	15.97	1.050	1223.9	60703.0	1.37000
.029712	.010740	94.3	43.3	1.8430	3.7069	31.50	31.50	16.06	1.067	1223.9	60703.0	1.37000

Figure 10. Natural draft cooling tower design output.

```
INTEGRATION NUMBER  1 COMPLETE

      MASS BALANCE:  L`2 - L`1 = G`s*(Y`2 - Y`1)
      ---- -------

                 LIQUID LOSS =   .02179 kg/m2-sec

                 VAPOR GAIN  =   .02179 kg/m2-sec

      ENERGY BALANCE:  L`2*Hal2 - L`1*Hal1 = G`s*(H`2 - H`1)
      ------ -------

         ENERGY LOST BY LIQUID =      72.1093 kJ/m2-sec

         ENERGY GAINED BY GAS  =      72.1099 kJ/m2-sec

         PERCENT DIFFERENCE BASED ON LIQUID  =    .0 %

         NEW L PRIME 1 = 1.8212102          DIF =   .00001022

         NTG =   .3833
```

Figure 10, continued.

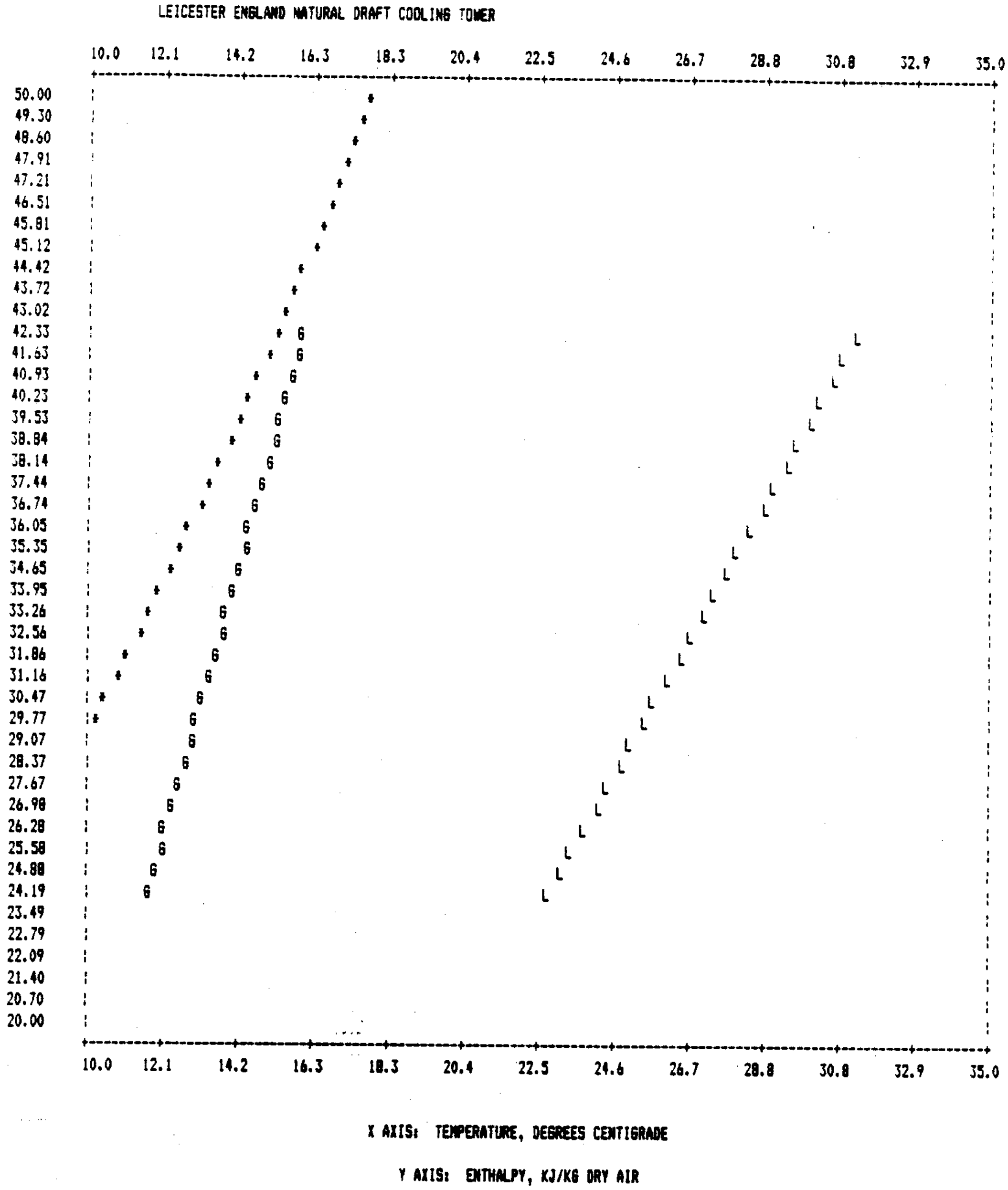


Figure 10, continued.

C. Packed Column Designs

Data for both mechanical and natural draft towers was available from the literature, but in the case of packed columns, no presentations of actual data could be found. The example shown is a slight modification of data taken from the Shulman (1959) models as presented in the 1980 version of Treybal, pages 202 through 209.

In the case of the Shulman model, calculations are available for the mass transfer coefficients for each increment of height, so they are recalculated each time. Since the notation and computations of the coefficients are complex, the user has the option of printing an example of the calculations for an interval. Figures 15 and 16 present an example of these results.

In the case of packed columns, loading, pressure drop, and flooding data are critical. For this case, flooding and pressure drop data for a particular design packing choice are given from the methods provided from Eckert (1975). The program uses spline functions to reproduce the curves, then interpolates among the curves for a particular value of X and Y. Flooding and pressure drop data are printed out with the tower heading design as shown in Figure 11. Table 4 presents the input and design output values for this example, and figures 11 and 12 show the design output.

Table 4. Packed column input and design summary.

Inputs:

TL2 = 45.0 deg. C
TL1 = 32.0 deg. C
TG1 = 36.0 deg. C
L'2 = 1.16 kg/m^2-sec
G'1 = 0.987 kg/m^2-sec
Y'1 = 0.0182
Delta-Z = 0.05 m
Packing choice: #5, 0.5 in Berl saddles (see User's manual)
$k_{Y'}a$ = Shulman methods
T_i Calculated for each interval

Outputs:

Packed height, meters 2.318

L'1 = 1.137 kg/m^2-sec

Exit gas relative humidity 97.0%

Number of iterations required
for 2 place accuracy of L'1 2

NTG = 1.894

MASS AND HEAT TRANSFER COEFFICIENT CALCULATIONS
==

Primary Reference : Shulman et al, "Performance of Packed Columns", series of 5 articles, AIChE Journal, 1959 5(3) p. 290-294 (last article)

Adapted By: Treybal, Robert E. Mass Transfer Operations, 3rd Edition, 1980 p. 196-209

SYMBOL	UNITS	DEFINITION
Phi	Dimensionless	Holdup -- represents volume liquid/volume packed column
Ds	meters	Diameter of an equivalent sphere
Beta	Dimensionless	Exponent Used in holdup calculations
E	Dimensionless	Epsilon, dry bed voidage
a	m2/m3	interfacial area
jd	Dimensionless	j factor for mass transfer
jh	Dimensionless	j factor for heat transfer
kY	W/m2-K-Delta Y`	mass transfer coefficient
hg,hl	W/m2-K	gas, liquid heat transfer coefficient
Pr	Dimensionless	Prandtl number
Cp	N-m/Kg-K	thermal heat capacity
Nu	Dimensionless	Nusselt Number
kthl	W/m-K	liquid thermal conductivity
mu	Kg/m-sec	viscosity
Sc	Dimensionless	Schmidt Number
m,n,p	Dimensionless	exponents used in interfacial area calculations
Rhog	Kg/m3	gas phase density

SUBSCRIPT	REFERS TO
Lo	operating or moving liquid
Ls	static liquid
Lt	total liquid
W	water
A	absorption
V	vaporization
l	liquid
g	gas

VARIABLES AND OPERATIONAL PARAMETERS
====================================

VARIABLE	VALUE	VARIABLE	VALUE
Packing Choice	BERL SADDLES	Prg	.70
Nominal Size (mm)	13	Prl	5.15
L Prime	1.14	Scg	.60
G Prime	.99	Cpg	1004.1
G (G Prime/28.97)	.0341	mug	.187848E-04
Liquid Temp	32.00	mul	.766229E-03
Interface Temp	31.50	kthl	.622201E+00
Gas Temp	36.00	Rhog	1.152
Film Temp	33.75		

Note: all gas phase variables are evaluated at the film temperature -- T Film = (TG + TI)/2.0

Figure 11. Packed column design calculations.

```
HOLDUP CALCULATIONS
====== ============

Treybal, Table 6.5, p. 206


Epsilon  =     .630
L Prime  =    1.14  Kg/m2-sec
DS       =     .3162 meters
Beta     =     .9781

Phi-LsW  =     .0003
Phi-LtW  =     .0168
Phi-LoW  = (Phi-LtW) - (Phi-LsW)
         =     .01649
```

```
INTERFACIAL AREA CALCULATIONS
=========== ==== ============

Treybal, Table 6.4, p. 205


L Prime =  1.14 Kg/m2-sec
  m      = 16.28
  n      =   .0529
  p      =   .761

aAW = (m*(808*G'/Rhog**0.5)**n)*L'**p
    =  25.47 m2/m3


aVW = 0.85*aAW*(Phi-LtW/Phi-LoW)
    =  22.04 m2/m3
```

```
MASS TRANSFER EQUATIONS
==== ======== =========

LIQUID PHASE (Used to determine hl)
------ -----

       (       (Ds*L')        )
  Nu = (25.1*(-----)**0.45)*(Prl**0.45)
       (       ( mul )        )

GAS PHASE
--- -----
           (Ds*G Prime )
  jd = 1.195*(-----------)**(-0.36)
           (mug*(1-ELo))


      jd =   kY*Scg**(2/3)
             -------------
                   G


HEAT TRANSFER EQUATIONS
==== ======== =========

CHILTON COLBURN ANALOGY:
------- ------- -------

                   hg
      jd = jh =  ----- *Prg**(2/3)
                  Cp*G'

LEWIS RELATION:
----- --------

        hg
       ----  = 950 W-m/Kg-K
        kY
```

```
EQUATIONS EVALUATED
========= =========

Epsilon  =   .630

ELo = E - (Phi-LtW)
     =       .613

jd  =     .02567

kY  =      .03559  Kg/m2-sec-Delta Y'

Nu  =     906.77

hg, Chilton Colburn
     =     32.1  W/m2-K

hg, Lewis
     =     33.8  W/m2-K

hl, from Nu = hl*Ds/kthl
     =    1784.2 W/m2-K

Corresponding Volumetric Coefficients
============= ========== ============

kYaVW =   .7844 Kg/m3-sec-Delta Y'
hgaVW (CC) =     708.6  W/m3-K
hlaVW      =   39328.9  W/m3-K
hgaVW (Lewis) =     745.2  W/m3-K
```

Figure 11, continued.

```
                    PACKED COLUMN/COOLING TOWER DESIGN

                          INTEGRATION NUMBER  1


TL2 =  45.00                  TG2  unknown          VARIABLE      UNITS
L'2 =   1.160   ====>X  X====>  Y'2  unknown          ----------------------
                     X  X                             TEMPERATURES  DEGREES C
                     X  X                             FLOW RATES    kg/m2-sec
                  XXXXXXXXXX
       Z PLUS     X   2.   X
      DELTA Z ----X--------X----
                  X        X     DELTA Z =  .050 meters
            Z ----X--------X----
                  X        X                          DESIGN PARAMETERS
                  X   1.   X                          ------------------------------------------
                  XXXXXXXXXX
                     X  X                             CRITICAL RELATIVE HUMIDITY  =  100.0
TL1 =  32.00         X  X     TG1  =  36.00           L/G RATIO =  1.18
L'1   unknown   <====X  X<====  Y'1  =    .0182
                              G'1  =   .987           PRESSURE DROP  =  530.0 (N/m2) per m packing
                              G'S  =   .969           FLOOD POINT    = 2042.0(N/m2) per m of packing
```

GAS STREAM MASS TRANSFER			PROCESS ENERGY AND MASS DATA			TEMPERATURES IN DEGREES CENTIGRADE				HEAT AND MASS TRANSFER COEFFICIENTS		
SATURATION HUMIDITY (kg/kg)	BULK GAS HUMIDITY (kg/kg)	RELATIVE HUMIDITY (%)	BULK GAS ENTHALPY (kJ/kg)	LIQUID RATE (kg/m2s)	GAS RATE (kg/m2s)	LIQUID (C)	INTERFACE (C)	BULK GAS (C)	HEIGHT (m)	GAS hga (W/m3sK)	LIQUID hla (W/m3sK)	MASS kYa (kg/m3s)
.029721	.018200	48.5	82.9	1.1370	.9870	32.00	31.50	36.00	.000	708.6	39328.9	.78443
.030082	.018664	50.1	84.0	1.1374	.9866	32.21	31.71	35.85	.050	708.6	39328.9	.78443
.030448	.019124	51.7	85.0	1.1379	.9870	32.41	31.91	35.71	.100	709.1	39349.4	.78492
.030820	.019581	53.3	86.0	1.1383	.9875	32.62	32.12	35.58	.150	709.5	39369.8	.78541
.031197	.020035	54.8	87.1	1.1388	.9879	32.83	32.32	35.46	.200	710.0	39390.0	.78590
.031581	.020487	56.3	88.1	1.1392	.9883	33.04	32.53	35.36	.250	710.5	39410.1	.78638
.031971	.020936	57.8	89.2	1.1397	.9888	33.25	32.74	35.27	.300	711.0	39430.1	.78687
.032368	.021383	59.3	90.3	1.1401	.9892	33.46	32.94	35.18	.350	711.4	39450.1	.78736
.032773	.021829	60.7	91.3	1.1405	.9897	33.67	33.15	35.11	.400	711.9	39469.9	.78784
.033184	.022273	62.2	92.4	1.1409	.9901	33.89	33.37	35.04	.450	712.4	39489.8	.78833
.033604	.022716	63.5	93.5	1.1414	.9905	34.11	33.58	34.99	.500	712.9	39509.6	.78882
.034032	.023159	64.9	94.6	1.1418	.9909	34.33	33.79	34.95	.550	713.4	39529.3	.78931
.034468	.023602	66.2	95.7	1.1422	.9914	34.55	34.01	34.91	.600	713.9	39549.1	.78979
.034913	.024045	67.5	96.8	1.1427	.9918	34.77	34.23	34.88	.650	714.4	39568.9	.79029
.035368	.024489	68.8	97.9	1.1431	.9922	35.00	34.45	34.86	.700	714.9	39588.7	.79078
.035833	.024933	70.0	99.0	1.1435	.9927	35.23	34.67	34.85	.750	715.4	39608.6	.79127
.036309	.025379	71.2	100.2	1.1440	.9931	35.46	34.90	34.85	.800	715.9	39628.5	.79177
.036795	.025826	72.4	101.3	1.1444	.9935	35.69	35.12	34.86	.850	716.4	39648.4	.79227
.037293	.026276	73.6	102.5	1.1448	.9940	35.93	35.35	34.87	.900	717.0	39668.5	.79278
.037804	.026728	74.7	103.7	1.1453	.9944	36.17	35.59	34.89	.950	717.5	39688.7	.79329
.038327	.027183	75.8	104.9	1.1457	.9948	36.41	35.82	34.92	1.000	718.0	39709.0	.79380
.038864	.027641	76.9	106.1	1.1462	.9953	36.66	36.06	34.95	1.050	718.6	39729.4	.79432
.039415	.028103	77.9	107.3	1.1466	.9957	36.91	36.30	35.00	1.100	719.1	39750.0	.79484
.039982	.028569	79.0	108.6	1.1471	.9961	37.17	36.55	35.05	1.150	719.7	39770.8	.79537
.040564	.029040	79.9	109.8	1.1475	.9966	37.43	36.80	35.10	1.200	720.3	39791.8	.79591
.041163	.029516	80.9	111.1	1.1480	.9970	37.69	37.05	35.16	1.250	720.9	39812.9	.79645
.041781	.029997	81.9	112.4	1.1484	.9975	37.96	37.31	35.23	1.300	721.5	39834.4	.79700

Figure 12. Packed column design output.

.042417	.030485	82.8	113.8	1.1489	.9980	38.23	37.57	35.31	1.350	722.1	39856.0	.79756
.043073	.030980	83.7	115.1	1.1494	.9984	38.51	37.83	35.39	1.400	722.7	39878.0	.79812
.043751	.031482	84.6	116.5	1.1499	.9989	38.79	38.10	35.48	1.450	723.3	39900.2	.79870
.044451	.031991	85.4	117.9	1.1504	.9994	39.08	38.38	35.58	1.500	724.0	39922.8	.79928
.045176	.032510	86.2	119.4	1.1509	.9999	39.37	38.66	35.68	1.550	724.6	39945.8	.79988
.045926	.033037	87.1	120.8	1.1514	1.0004	39.67	38.94	35.78	1.600	725.3	39969.1	.80048
.046703	.033575	87.8	122.3	1.1519	1.0009	39.98	39.23	35.90	1.650	726.0	39992.8	.80110
.047510	.034123	88.6	123.9	1.1524	1.0014	40.30	39.53	36.02	1.700	726.7	40017.0	.80173
.048347	.034683	89.4	125.5	1.1530	1.0019	40.62	39.83	36.15	1.750	727.4	40041.6	.80237
.049218	.035255	90.1	127.1	1.1535	1.0024	40.95	40.14	36.28	1.800	728.1	40066.8	.80303
.050125	.035840	90.8	128.7	1.1541	1.0030	41.29	40.46	36.42	1.850	728.9	40092.5	.80370
.051070	.036440	91.5	130.4	1.1547	1.0035	41.63	40.79	36.56	1.900	729.6	40118.8	.80439
.052056	.037056	92.2	132.2	1.1553	1.0041	41.99	41.12	36.71	1.950	730.4	40145.7	.80510
.053087	.037687	92.9	134.0	1.1559	1.0047	42.36	41.46	36.87	2.000	731.3	40173.3	.80582
.054165	.038337	93.6	135.8	1.1565	1.0053	42.74	41.81	37.04	2.050	732.1	40201.6	.80657
.055295	.039006	94.2	137.7	1.1572	1.0059	43.13	42.18	37.21	2.100	732.9	40230.6	.80734
.056482	.039695	94.9	139.7	1.1578	1.0065	43.53	42.55	37.38	2.150	733.8	40260.5	.80813
.057728	.040407	95.5	141.7	1.1585	1.0071	43.94	42.93	37.57	2.200	734.7	40291.3	.80894
.059041	.041142	96.1	143.8	1.1592	1.0078	44.37	43.32	37.76	2.250	735.7	40323.1	.80979
.060426	.041904	96.8	146.0	1.1600	1.0085	44.82	43.73	37.96	2.300	736.7	40355.9	.81066
.060997	.042214	97.0	146.9	1.1603	1.0097	45.00	43.90	38.04	2.320	737.7	40389.8	.81156

INTEGRATION NUMBER 1 COMPLETE

MASS BALANCE: L'2 - L'1 = G's*(Y'2 - Y'1)

LIQUID LOSS = .02328 kg/m2-sec

VAPOR GAIN = .02328 kg/m2-sec

ENERGY BALANCE: L'2*Hal2 - L'1*Hal1 = G's*(H'2 - H'1)

ENERGY LOST BY LIQUID = 66.1315 kJ/m2-sec

ENERGY GAINED BY GAS = 61.9826 kJ/m2-sec

PERCENT DIFFERENCE BASED ON LIQUID = 6.3 %

NEW L PRIME 1 = 1.1367219 DIF = .00027812

NTG = 1.8966

Figure 12, continued.

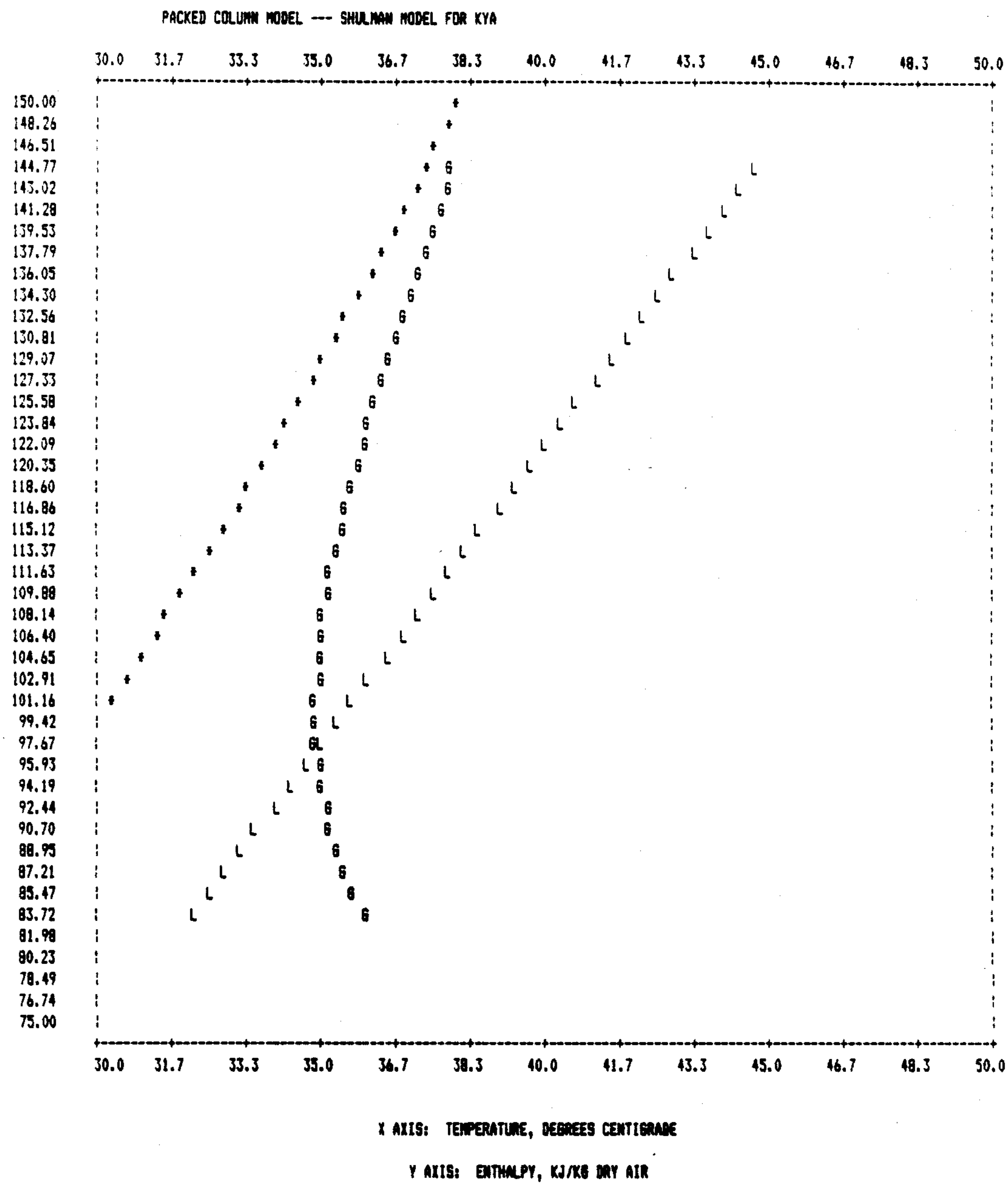


Figure 12, continued.

The major difference between this design and either of the two previous designs is that the mass transfer coefficient varies within the design; the magnitude of the change is slight, however, only 3% for this design which had little effect on the overall tower height when the same example was run with the mass transfer coefficient fixed at the value at the bottom of the column.

Another interesting feature about this design is that in the lower part of the column, the interface temperature is below both the liquid and gas temperatures. As Figure 23, shows, however, this is correct; the interface conditions are determined by the slope of $-h_L a/k_{Y'} a$, so the interface temperature is always below the liquid temperature. Since the wet bulb temperature of the liquid at 50% relative humidity and 36 degrees (the entering gas conditions) is approximately 26 degrees, as long as the exit liquid temperature is above this value the conditions shown are reasonable, although they seem counter intuitive.

Extension Of The Model To Other Areas

The design model as configured was intended to teach undergraduate students the major components of cooling tower design without spending lots of time on the numerical solution of the design equations. The design equations were written in general form, however, which means that they have applications to any condition which satisfy the assumptions in the model. Three applications will be discussed here: (A) Determination of mass transfer coefficients, (B) Applications to humidification design, and (C) Multiple component mixtures.

A. Determination of $k_{Y'}a$

In this application, actual performance data from the column are known, and the aim is to determine the mass transfer coefficient. Cases where this need arises include manufacturers who are evaluating packing configurations and materials; with reference to Figure 4, the only unknown is the mass transfer coefficient; the packing height is already known.

Solution to this case is very simple; the program should be run on a trial and error approach. Using the known entrance and exit conditions, choose a value for the mass transfer coefficient which yields a design that satisfies both the flow rates and temperatures, as well as being in agreement with the packing height.

Most expressions for mass transfer coefficients are given as a power function of the liquid to gas flow ratios (see equation 1.3). To obtain this function from this program, the user must have performance data for a variety of liquid and gas flows, then solve the design program to obtain the transfer coefficient for each set of conditions. From these data a graph of the mass transfer coefficient versus L/G ratio will yield the desired exponent for the power function.

B. Humidification Design

The term "Cooling Tower" is distinguished from "Humidification Equipment" only by the application of the equipment for an intended use; the major energy transfer which causes the water to be cooled in a tower comes from evaporation, resulting in humidification. It is only a matter of perspective whether cooling a liquid or humidifying a gas is the goal; one is not separate from the other.

Humidification equipment is designed to yield a given flow of gas with known temperature and humidity; thus, the exit gas parameters are either known or specified, and less is known about the liquid stream (typically TL1 is unknown).

Thus, a change in humidity (a humidification "load") is known rather than a drop in liquid temperature (a cooling "load").

Similar to the previous case, this solution requires a trial and error approach, but is more straight forward than the search for a mass transfer coefficient. The program is set up for cooling designs such that termination occurs when TL2 is obtained; the only variation here is that the program will not terminate for the desired Y'2, so the user will have to run the model with several tries of TL2 until the correct exit value of Y'2 is obtained. One way to reduce the number of iterations is to run the program with two or three guesses for TL2, then plot TL2 vs the Y'2 obtained in each case, and interpolate at the target value of Y'2 to improve the guess for TL2.

C. Multiple Component Mixtures

Stripping components from a gas stream or eliminating trace contaminants with high vapor pressures from a liquid stream are two major examples of applications which involve multiple component mixtures.

The major obstacle or limitation in this design program is that λo, the latent energy of evaporation, is responsible for the majority of the energy transfer which results in the liquid stream being cooled, and is numerically satisfied only for the air-water system. If the energies of evaporation, solvation, or other chemical reactions and phase changes which occur in these cases are not large, then the program can be used to predict the behavior of the streams and the packing height required. If the energy of mixing in a stripping operation is large, however, the errors induced can be quite large.

Similarly, the enthalpy driving forces between the interface and the bulk gas are the basis for the packing height integration; if the gas stream enthalpy cannot be calculated from the equations developed in section II, large errors will be induced.

The last problem with multiple component mixtures is that the goal of such structures is to perform the stripping operation, for example, yet this program tells nothing about the components other than the air and the water. If performance data on these aspects are known from some other method, however, then the program can be used either as a design or simulation method.

IV. SUMMARY AND CONCLUSIONS

As the examples have shown, the design program can be easily applied to a variety of situations provided reasonably accurate information is known about the design or simulation needed. Since the differential equations were developed in general form, the user has the ability to investigate the effect of any of the assumptions usually made to simplify the equations used, and since the program itself is interactive, it can be interrupted and redirected for designs which are not progressing to the desired result. The greatest advantage of the program, however, is that the user gains practical experience with the effect of any design parameter, the computer performing the numerical computations which usually take the majority of the student's time. By watching the results of choosing a particular design option or parameter, a student can develop an intuitive understanding for the components of humidification design without the need for time consuming calculations. In the case of cooling tower design, the computations are complex enough that without such an approach, an undergraduate student has little more than an introduction to the role various components play in the design process.

As the examples tested have shown, the greatest contribution to the height of fill required comes from the range of conditions under which the tower must perform, not from errors within the assumptions made in the development of the design equations. Two of these, the mass transfer coefficient and the inlet gas humidity and temperature, are particularly crucial. As figure 11 shows, the slope of these two parameters on fill height is the greatest, ranking them first and second, respectively, in order of importance. Obviously, the liquid and gas flow rates also directly impact the tower performance, both directly as "load" terms showing the amount of energy which must be removed from the liquid stream, but also as they affect the value of the mass transfer coefficient, as shown by the familiar power expression given in equation 1.4.

Most of the parameters just discussed, with perhaps the exception of the entering gas relative humidity, should be expected to be provided in a design case to determine the range of operating conditions under which the tower needs to be able to perform. The designer, therefore, should be able to pick a "worst case" set of values from which to base the calculations for fill height. In this case the other assumptions need to be reviewed, specifically those of no liquid evaporation and no liquid phase temperature gradient.

As the design plots show, for the cases studied here the role of liquid evaporation had little effect. As the NTU integration shown on Figure 2 demonstrated, the length of the line from the liquid conditions to the saturation curve determines the height of fill required; any curvature caused by changing liquid flow would affect the integration, but for typical cases the line is essentially straight. The only case that curvature could be important is if the operating line is very near the saturation line; minor changes in inlet gas humidity would then have major effects on tower performance. In most design applications this error could be ignored.

Figure 11 also explains why the assumption of no liquid phase temperature gradient is also reasonable. With reference to any of the designs studied here, the value of $-h_La/k_{Y'}a$ is very large; in every case studied the ratio of these two numbers is so great that little, if any, liquid phase temperature gradient could be expected in the column. In the design cases in which h_La was varied, several orders of magnitude of change resulted in less than a 10% difference in overall height. Only when h_La was dropped an order of magnitude or more below the values predicted by the Chilton-Colburn analogy did the height rise, but for all practical values of h_La there was little effect.

Given the relatively small importance of the errors contributed by the assumptions commonly used in these designs, it is not unreasonable to ask why cooling tower manufacturers do not make further use of design models such as these. The answer lies in the variability and importance of the mass transfer coefficient to the tower design. As previously shown, the mass transfer coefficient is the principle factor in determining the tower height, and since the performance data for prototype and existing towers show variations of 25% or more from test to test, it is the uncertainty in the mass transfer coefficient itself, not the design programs, which force large safety factors into tower designs. Since the mass transfer coefficient is directly related to the ratio of the liquid to gas flow rates, it is the way in which the gas and liquid contact each other, and the variability in the contact process, which determines the mass transfer coefficient, and thus the tower height needed. A manufacturer with experience with a particular type of fill and gas/liquid distribution system would have a much higher chance of success applying their direct experience to a new design rather than trying to develop a generally applicable model.

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APPENDICES

Appendix A1. Derivation Variable List

The variables listed in this appendix are used in the derivation of the design equations in section II, Model Development.

Notes:

1. Letter and Number Case

Upper case letters generally denote actual, known, or specified information; lower case is often used in a derivation. For example, TL1 specifies the actual liquid temperature at the bottom of the tower, whereas t_L is used in the general form of the differential equations to represent the liquid temperature at any point.

2. Subscripts

Subscripts are used throughout the derivation to describe position (eg z, z+dz), phase (eg l,liquid, or g for gas), or reference, such as the various subscripts on K, the mass transfer coefficient, showing the type of coefficient.

3. List of variable definitions

a	Specific interfacial area, m^{-1}
a_h	Specific interfacial area for heat transfer, m^{-1}
a_m	Specific interfacial area for energy transfer, m^{-1}
C_L	Liquid phase heat capacity, constant at 4178 J/kg-K
C_s	Heat capacity of the gas phase, including the water vapor, per unit mass of dry gas; also called the humid heat, J/kg-K
Cp	Heat capacity of the dry air, J/kg-K
δ(x)	Differential element of x, eg m = differential element of mass, kg
d(x)	Derivative of variable (x), eg dt = derivative of temperature
De	Hydraulic diameter for air flow, meters
D_{ab}	Diffusivity of species a in species b, m^2/sec
	Delta, used to express a finite difference in contrast to a differential amount d(x).
G	Gas flow rate, kg/sec
G'	Superficial gas flow, kg/sec-m^2
G's	Superficial gas flow of dry air, kg/sec-m^2

List of variable definitions, continued:

h	Convective heat transfer coefficient, W/m^2-K
h'	Convective heat transfer coefficient, W/m^2-K
h_g	Gas phase heat transfer coefficient, W/m^2-K
h_L	Liquid phase convective heat transfer coefficient, W/m^2-K
H'	Enthalpy of the bulk gas mixture per unit mass dry gas, J/kg
Ha	Enthalpy of species a per unit mass dry gas, J/kg
Ha_L	Enthalpy of species a in the liquid phase, J/kg
$Ha_{L,i}$	Enthalpy of the liquid at the interface temperature, J/kg
H'_i	Enthalpy of the bulk vapor at the interface temperature, J/kg
j_D	J factor for mass transfer, dim
j_H	J factor for energy transfer, dim
k_{th}	Thermal conductivity of the gas, W/m-K
k_Y	Mass transfer coefficient, kg/m^2-sec (Y/Y)
$k_{Y'}$	Mass transfer coefficient, kg/m^2-sec (Y'/Y')
Ka	Mass transfer coefficient, lb/hr-ft^2 (english units, Merkel's notation)
KaV/L	Tower characteristic, dimensionless (Merkel's notation)
L	Liquid mass flow rate, kg/sec
L'	Superficial liquid flow rate, kg/m^2-sec
L'1	Superficial liquid flow rate at the bottom of the column, kg/m^2-sec
L'z	Superficial liquid flow rate at an arbitrary height z, kg/m^2-sec
λ_o	Latent heat of vaporization, 2,502,300 J/kg
M	Slope of a line, delta-y/delta-x
Ma	Molecular weight of species a, kg/mole
Mb	Molecular weight of species b, kg/mole
p_a	Partial pressure of species a, dimensionless
p_b	Partial pressure of species b, dimensionless
P	Pressure, pascals
Pr	Prandtl number, dimensionless
Pr_g	Prandtl number for the gas mixture, dimensionless
Re	Reynolds number, dimensionless
Sc_g	Schmidt number based on the gas mixture, dimensionless

List of variable definitions, continued:

t_i	Temperature at the interface, degrees
t_g	Temperature of the bulk gas, degrees
t_L	Temperature of the liquid, degrees
t_o	Reference temperature for energy of evaporation, degrees
T	Temperature, degrees
TG1	Temperature of the gas at the bottom of the column, degrees
V	Packing height, ft (Merkel's notation)
Y'	Absolute humidity, lbm vapor/lbm dry air
Z,z	Height, meters

Greek Symbols:

ρ	Density, kg/m^3
ρ_g	Density of the gas phase, kg/m^3
ρ_L	Density of the liquid phase, kg/m^3
μ	Viscosity, kg/m-sec
μ_g	Viscosity of the gas phase, kg/m^3
μ_L	Viscosity of the liquid phase, kg/m^3

APPENDIX A2. User's Manual

Note: The User's manual was intended to be used to assist the student directly running the program. This caused a great deal of redundancy with the main body of the thesis, since the student using the program will not have the thesis for reference.

Appendix A2 Table Of Contents

Introduction

This manual describes the use of a design program which considers simultaneous mass and energy transfer in direct contact counterflow heat exchangers for the air - water system. The two types of exchangers encountered are either packed beds or cooling towers, the design for either of which is identical.

Figure 1 illustrates a tower diagram. In general, the unknowns are TG2, Y'2, L'1, and Z, the height of packing required. By specifying values for the required inputs, all four of the unknowns will be calculated by the program. The section of this manual entitled "Before You Begin" discusses the development of the necessary inputs.

The program is completely menu driven, and interacts frequently with the user to design a piece of equipment using a trial and error approach. At almost any point in the program,the user may interrupt calculations to change variables, restart the program, or abandon calculations and plot the design up to that point in order to study its progress.

An iterative technique is used to solve the equations over an increment of height delta-Z (ΔZ) chosen by the user. The program is complete on a single disc, and is run by a file called "Humid". To use this program, an IBM or compatible machine with 126K of central memory is required. The program will require an Intel 8087 math coprocessor. The printer must be associated with the first port, that is, it must be ready to respond to an "LPT1" command. This is the standard configuration for IBM PC's when connected to a single printer.

The information and required inputs are described in the section entitled "Before You Begin", and this section should be studied next. The section entitled "Running The Program" explains in detail how to respond to the prompts during execution, and the section entitled "Examples" provides an example for each of the two major types of designs being covered- cooling towers and packed beds. It is recommended that you become familiar with the program by reading "Before You Begin" and "Running The Program" <u>before</u> trying to run the examples. In particular, "Before You Start" reviews the theory necessary to understand some of the choices encountered in the program.

Before You Start

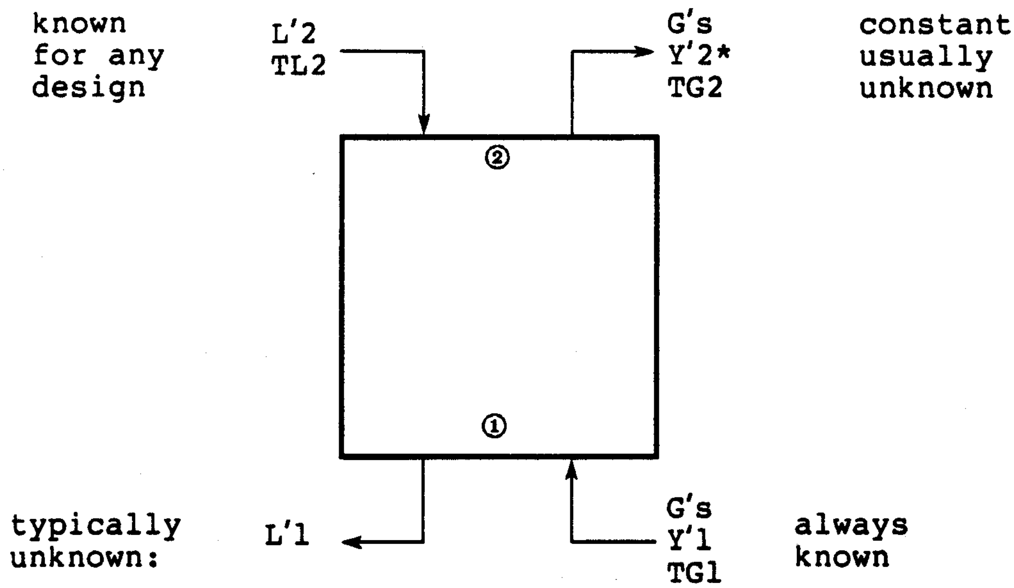
As shown in Figure 1, the required inputs are TL2, TL1, TG1, L'2, G'1, and Y'1. This section explains how to prepare this information and discusses some of the other decisions offered to the user.

Temperatures

All temperatures are required in degrees Celsius. All the internal calculations will be performed in Kelvins, but the output (diagrams and the plot) are printed in degrees Centigrade. In the cooling tower literature, the term "cooling range" or just "range" is the difference between the inlet and the outlet liquid temperatures; only an inlet temperature and a range need be given. The inlet gas temperature, TG1, is the dry bulb temperature.

Flow Rates

The flow rates L' and G' are expressed per unit cross section area, which implies that the diameter of the tower must already be known. If you are fully designing a packed bed, the diameter calculations must be performed first, and are covered in most standard design manuals. To simulate an existing cooling tower, divide the mass flow rates by the "plan area", or the cross sectional area of the fill. The final units should be kg/m2-sec.



specified: TL1

Variable	**Status**
G's	Known
Y'2*	Unknown
TG2	Unknown
Y'1	Known
TG1	Known
L'2	Known
TL2	Known
L'1	Unknown
TL1	Known

* specifying Y'2 is a humidification design problem.

Figure A1. Contacting equipment schematic.

Gas Humidity (Y'1)

The entering gas humidity is expressed in absolute mass terms as kg vapor/kg dry air, and is dimensionless. A psychrometric chart, Figure 3, is provided on the next page to determine this value, provided two pieces of information are known. In cooling tower design, the two pieces of information are the dry and wet bulb temperatures of the entering air stream. Auxiliary data at the end of the User's Manual contains reprints of charts which can assist you in designing a piece of equipment for the United States by providing design dry and wet bulb temperatures by geographic location. This information can be used to estimate the unknown parameters in simulating the performance of an existing unit.

The term "approach" in the cooling tower industry refers to the difference between the wet bulb temperature of the incoming air and the exit temperature of the liquid. This value is a measure of the degree of difficulty in cooling the liquid since the wet bulb temperature represents a theoretical minimum to which the water can be cooled. By knowing the inlet water temperature, the range, and the approach, therefore, all the temperatures as well as the entering gas humidity can be determined.

Estimating Evaporation Losses

The program takes into account evaporation losses as the liquid is cooled. The solution to a design problem is a trial and error process based on the liquid flow rate. The program requires either an initial guess of L'1, or an initial estimate of the evaporation loss expressed as a percentage of L'2 entered in decimal form. Integration proceeds upward until TL2 is exceeded, at which time the program stops and asks whether you wish to perform another trial. An improved value for L'1 is presented for use in the next iteration. If you wish to continue with the improved value, enter a 0 (zero) when the menu is displayed, and the program will proceed.

When the initial values for the program are being requested, you may enter an estimate for L'1 directly, in which case the units are Kg/m2-sec, or you may provide an estimate of the percentage loss expressed in decimal form (eg 0.02, not 2%). Typical evaporation rates are 1% - 5% in cooling towers.

Delta Z

Delta Z is the increment height in meters. For cooling towers, values of 0.1 or even 0.2 meters are appropriate; for packed columns, values nearer 0.025 m (~1 in.) are more realistic. Delta Z is one of the parameters which can be varied during execution, and often needs to be made smaller as the top of the column is approached. Early trials with larger delta Z may aid in determining L'1, then a final run may be made with a much smaller value for greater accuracy. Numerical integrations are very sensitive to the size of the increment chosen, and although the printout will be longer, best results are obtained when delta Z is chosen as small as tolerable.

Critical Humidity

As the gas stream proceeds up through the column, it is heated and gains mass from the liquid being cooled. Mass is transferred to the gas until saturation is achieved, at which time the program will stop and ask you for directions. Numerically, achieving 100% saturation will never occur, since the driving forces decay as the gas stream approaches saturation; practically, however, a design should not exceed 97% - 99% relative humidity. The industry simplifies the design by assuming that the exit gas is saturated. A value of 99% will insure against premature program termination; the critical humidity is also a value which may be changed during program execution.

Access Frequency

During the integration it may become apparent that the parameters specified may be unworkable, and there is no reason to continue. Another reason to interrupt the program is to correct a mistake made at the data entry point, or to change a non-critical parameter such as the access frequency itself or the critical humidity. In any case, the access frequency is the number of lines printed before the program can be halted; it represents the number of increments of delta Z which have been solved. The choices available when the access menu is displayed are described under the section "Running The Program". Generally, a frequency of 5 or 10 is appropriate; if no interruption is desired, set the value to 50 or 100.

Because of a limitation in the FORTRAN compiler, you will notice that if you choose a value of 10 for the access frequency, the program will stop printing after 9 lines are printed. The tenth line is in the print buffer, and will be printed _after_ the access menu selection is made. This may fool you a few times until you become used to it.

Interface Calculations

A very common assumption in the design of humidification equipment is that the interface temperature is equal to the liquid temperature. This implies that the liquid phase heat transfer coefficient is infinite, that no resistance to heat transfer occurs in the liquid phase. In most of the examples studied, this assumption is very nearly true, and to ease computational efforts, assuming that TI = TL is a standard design assumption.

Figure 4 illustrates the relationship between conditions in the liquid stream and the interface. A tie line with slope -hla/kY'a drawn from the point representing the liquid temperature at the enthalpy of the gas stream intersects the saturation curve at the interface temperature. As the ratio of hla to kY'a increases, this tie line approaches a vertical line, and in the limit, TI approaches TL. Note that since the slope is always negative, the interface temperature must always remain below the liquid temperature.

A value of hla is needed to solve the interfacial temperature only when this option has been chosen. When TI is assumed to equal TL, hla is not used by the program. Please keep this in mind when reading the section on mass and heat transfer coefficients.

Mass and Heat Transfer Coefficients

The mass and heat transfer coefficients required to solve the differential equations can be calculated five ways -- four techniques have been incorporated directly into the program, and the fifth choice allows the user to enter values directly. Of the four internal techniques, two methods are applicable to packed columns, and two are available for cooling towers.

For packed columns of Raschig rings and Berl saddles, the correlations of Shulman have been included. For Raschig ring calculations, choices are for 0.5, 1.0, and 1.5 inches; for Berl saddles, the choices are 0.5, 1.0, and 1.5 inches. In a series of articles entitled "Performance of Packed Columns", methods for predicting kY'a, hga, and hla were published for a wide variety of operating conditions. The user has the choice of having these values recalculated for each increment, or holding the values constant after evaluating them at the bottom of the column.

For cooling towers, kY'a can be calculated from the correlations provided by Lichtenstein and Norman. Both of these correlations were developed from small scale test towers, but the range of mass transfer coefficients predicted are in scale for full size cooling towers.

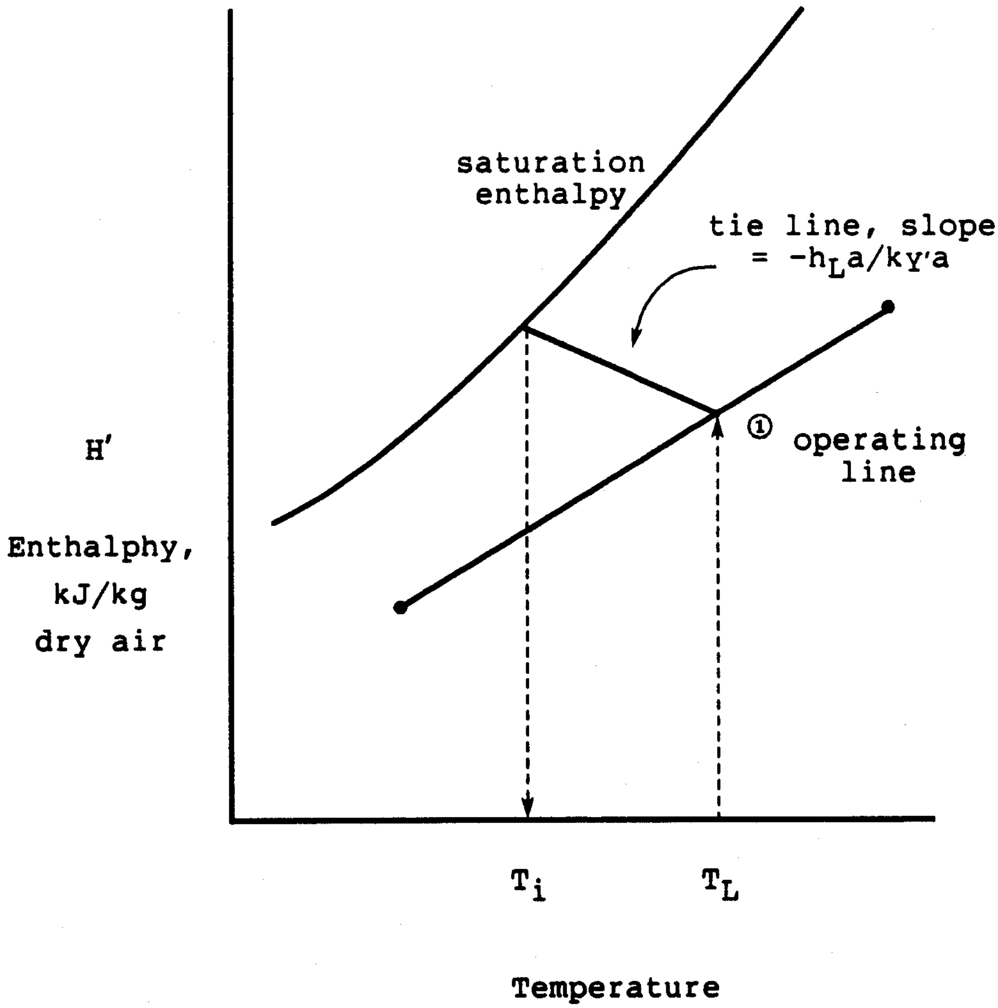


Figure A2. Interfacial temperature determination.

To complete the range of choices available, the user can enter kY'a directly. Table 1 presents a summary of the data and ranges for the mass transfer coefficients for both packed columns and cooling towers, and may be used as a guide in selecting an appropriate value. In order to simulate the performance of an existing unit, the Auxiliary Data section Number 2 provides the techniques for calculating kY'a from tower performance information such as the capacity coefficient.

Once the mass transfer coefficient has been determined, the gas and liquid phase heat transfer coefficients are evaluated. Gas phase heat transfer coefficients are predicted from kY'a by both the Chilton Colburn analogy and the Lewis relation, from which the user makes the final choice. When the user selects calculations for hga based on the lewis analogy, the value for kY'a will be varied such that the Lewis analogy is satisfied throughout the column.

In the case of the Shulman calculation techniques, the liquid phase heat transfer coefficient is calculated by formula; unfortunately, however, no correlations for hla in cooling towers are available since the assumption is made that hla is infinite, that TI=TL, as previously discussed. In order to provide an estimate for hla for cooling towers, hla for a packed column is always evaluated from the Shulman correlations, then used to extrapolate to cooling towers:

$$hla_{\text{cooling towers}} = hga_{\text{cooling towers}} \times (hla/hga)_{\text{packed columns}}$$

A liquid phase heat transfer coefficient is necessary only when TI is being calculated; if TI is assumed equal to TL, then the value of hla is ignored by the program.

The mass and heat transfer coefficients are handled separately in the program. The user chooses the method of calculating kY'a, then the heat transfer coefficients are presented, from which the user chooses the final values to be used before integration begins. If the Shulman method is used for a packed column, the above does not hold; once the Shulman method is chosen, the program proceeds directly to the integration routine. Two pages of calculations for the Shulman correlations may be printed out if desired.

Pressure Drop Calculations

For packed columns, flood point and pressure drop calculations are provided according to the method of Eckert. Calculated pressure drop in units of N/m2 per meter of packed height are printed before integration begins. The variation of pressure within the column is ignored, and is assumed equal to one atmosphere. Pressure drop calculations are not available for cooling towers due to the lack of available correlations.

Table A1. Packing choice numbers and data ranges.

Packing	Nominal Size mm	in	Packing Number Choice
Raschig Rings	13	0.5	1
	25	1.0	2
	38	1.5	3
	50	2.0	4
Berl Saddles	13	0.5	5
	25	1.0	6
	38	1.5	7

	L' kg/m2-sec		G's kg/m2-sec	
Correlation	min	max	min	max
Shulman	0.68	6.10	none specified	
Norman	1.26	3.82	1.36	4.08
Lichtenstein	0.48	4.08	0.90	2.28

NTU Integration

A common design approach to tower height is based on NTU, the number of transfer units. Labelled gas phase transfer units, tower height may be calculated by evaluating an enthalpy integral derived by assuming negligible liquid evaporation losses:

$$NTU = \int \frac{dH'}{H'_i - H'} \quad , \qquad \text{and } Z = NTU \times HTU,$$

where $HTU = G's/k_Y'a$

This integral, which is related to the area between the operating line and the saturation enthalpy line from point 1 to 2, Figure A3, is a measure of the difficulty of energy transfer. The number may be approximated by the number of times the average driving force divides into the enthalpy change. HTU is often provided in design guides and by packing manufacturers rather than $k_{Y'}a$, and has the simple dimensions of length.

The design program evaluates NTU by the trapezoidal rule after each increment of height, saves the information,and prints the resultant value at the end of each integration.

Printer - Compressed Print

The program sends a code to the printer instructing it to used compressed print type. Look in your printer manual and find the ASCII number corresponding to compressed print. The command in BASIC is CHR$(NUMBER), where NUMBER is the integer for compressed print. Many printers use 15 as this number. This number is the first thing requested by the design routine.

Labels

It is often useful to keep some notes about each run -- what the aim was, how the run varied, etc. You may label both the main calculations and title the plot. The main calculations will accept a maximum of nine lines of notes. Each line has a maximum of 100 characters, so write your note before you enter it. The program will ask first for the number of lines, then it will ask for each line. The data plot will only ask for a one line title.

Be vary careful about entering these notes -- you must start and end each line with an apostrophe ('), and no other apostrophes must be used in the line. I have also noticed that the program fails if a comma is used in the notes.

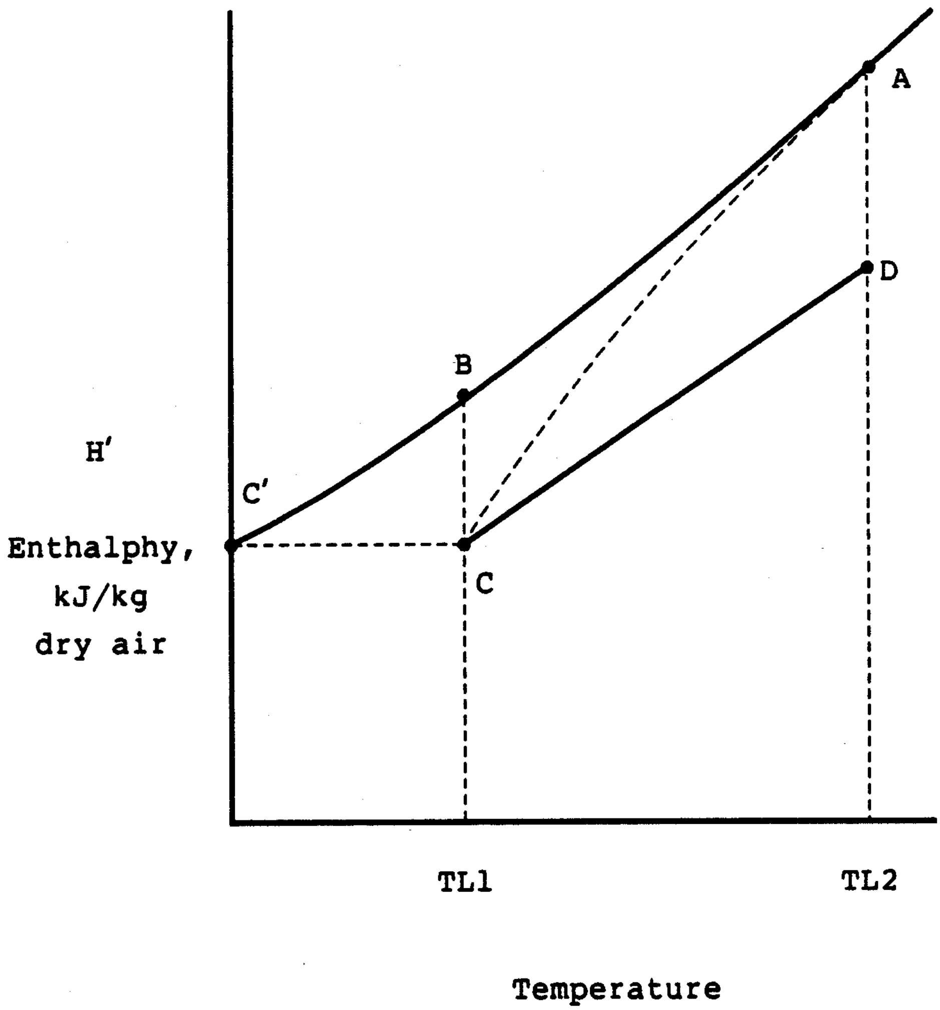


Figure A3. Enthalpy-temperature counterflow cooling diagram.

Problems

1. If you are asked for a value, and by mistake you press return without having entered the number, the program will not continue until the number is entered. Just enter the number and then press return, and the program will continue. When you press return by mistake, no message will be displayed, but the program will wait until it detects that a number has been entered.

2. If you enter the wrong number, or something major is going wrong, just press the keys marked "Ctrl" and "Break" at the same time. This is a Control-Break sequence, and the program will abort completely, and the A-prompt (A>) will appear. Type "Humid" to start again. All the work that you have done up to that point will be lost, but the program will not be harmed in any way.

Running The Program

1. Please be certain to have read the section entitled "Before You Begin" <u>before</u> running the design program.

2. At this point, the following values must be known:

   TL2, TL1, TG1
   L'2, G'1, Y'1
   Evaporation loss for 1st guess
   Delta Z
   Critical humidity
   Access frequency

3. In addition, you must have decided:

   1. How to calculate kY'a, and
   2. Whether to calculate TI from hla or assume that TI=TL

4. Turn on the computer and the printer, and make certain that the A - prompt (A>) is showing.

5. Place the design disc in the A drive, and type Humid, then press return.

6. A message will appear asking for the compressed print code number. Enter the number, then press return.

7. Wait while the data files are being read.

8. The primary input screen note will appear, and the program will request each of your data values. Enter each as requested, always following each value by a return.

9. The program shows a screen telling you which of the correlations for kY'a are valid for your choice of operating conditions. Choose a method for evaluating kY'a. The program will not stop you if you attempt to use one of the correlations which is out of range.

Note: Items 10 and 11 apply <u>only</u> to the Shulman calculations. For any of the other methods, continue with number 12.

10. If you chose the Shulman method, enter the packing number choice. See Table 1 for the selections. Next you will be asked whether to print two pages of example calculations. Respond with a zero or a one, then press return.

11. Proceed to item number 13.

12. A screen will appear showing kY'a and two values for each of hga and hla. Follow the instructions on the screen to choose the values to be used.

13. Enter the number of lines of notes you wish to print, then enter each line. Remember to enclose each note with a single apostrophe ('), and do not use any apostrophes or commas in the note. Follow each note by return.

14. After setting the printer to the top of a new page, the messages and a diagram will be printed summarizing your data, including pressure drop estimates and flood points for packed columns.

15. Once the data headings are printed, integration begins.

Note: At this point, the design integration routine is proceeding. From now on, the instructions chosen will determine how the program acts. The following subjects discuss the remaining options.

Access Menu

After the program has solved the number of increments specified by the access frequency, the program will halt, displaying the access menu, and will wait until one of the options has been chosen. To make a choice, type the number of your choice, then press return. The choices are:

<u>(0) Continue (No changes)</u> This means everything is okay, keep going. No action to be taken.

<u>(1) Stop here (go to plot section)</u> Stop integrating and plot the progress up to this point.

<u>(2) Delta Z</u> Continue integrating using a different value of delta Z. The new value to be used will be requested.

<u>(3) Critical Humidity</u> Continue integrating using a new value of critical humidity to terminate integration.

(4) Access Frequency Continue integrating using a new access frequency.

(5) Restart (Multiple Changes) Return to the primary inputs area. This starts the program over.

Note: Remember that one increment of height has been solved and is in the print buffer until after the access menu selection has been chosen.

Saturation Achieved

When saturation is achieved, generally either kY'a needs to be decreased, or the gas flow rate G' needs to be increased. A menu will appear, offering four choices including the two above plus a plot and a restart option. Make a choice to continue.

End of Integration

Integration proceeds until the liquid temperature exceeds TL2. The program then stops and prints out the mass and energy transfer information, and a menu is presented. Make a choice to continue. To continue the integration, you need an improved value for L'1. Refer to the printout. If L'2 was exceeded when integration ended, the next guess for L'1 needs to be lower than the previous value, and vice versa.

Plot Routine

The plot routine will ask you for a single line title. Remember to use an apostrophe to start and end your title; maximum length is 100 characters. A screen will appear showing the values necessary to include both the liquid and gas operating lines, as well as the saturation line. You need to enter the start and stop temperatures in degrees Centigrade, the start and stop enthalpies in kJ/kg. Enter the two values at the same time, separated by a comma (eg 30,64), then press return. If you want to include the saturation line, be sure to make the stop enthalpy above the minimum saturation enthalpy value shown on the screen. Figure 6 illustrates these values. You may replot the data several times by entering a 1 in response to the prompt.

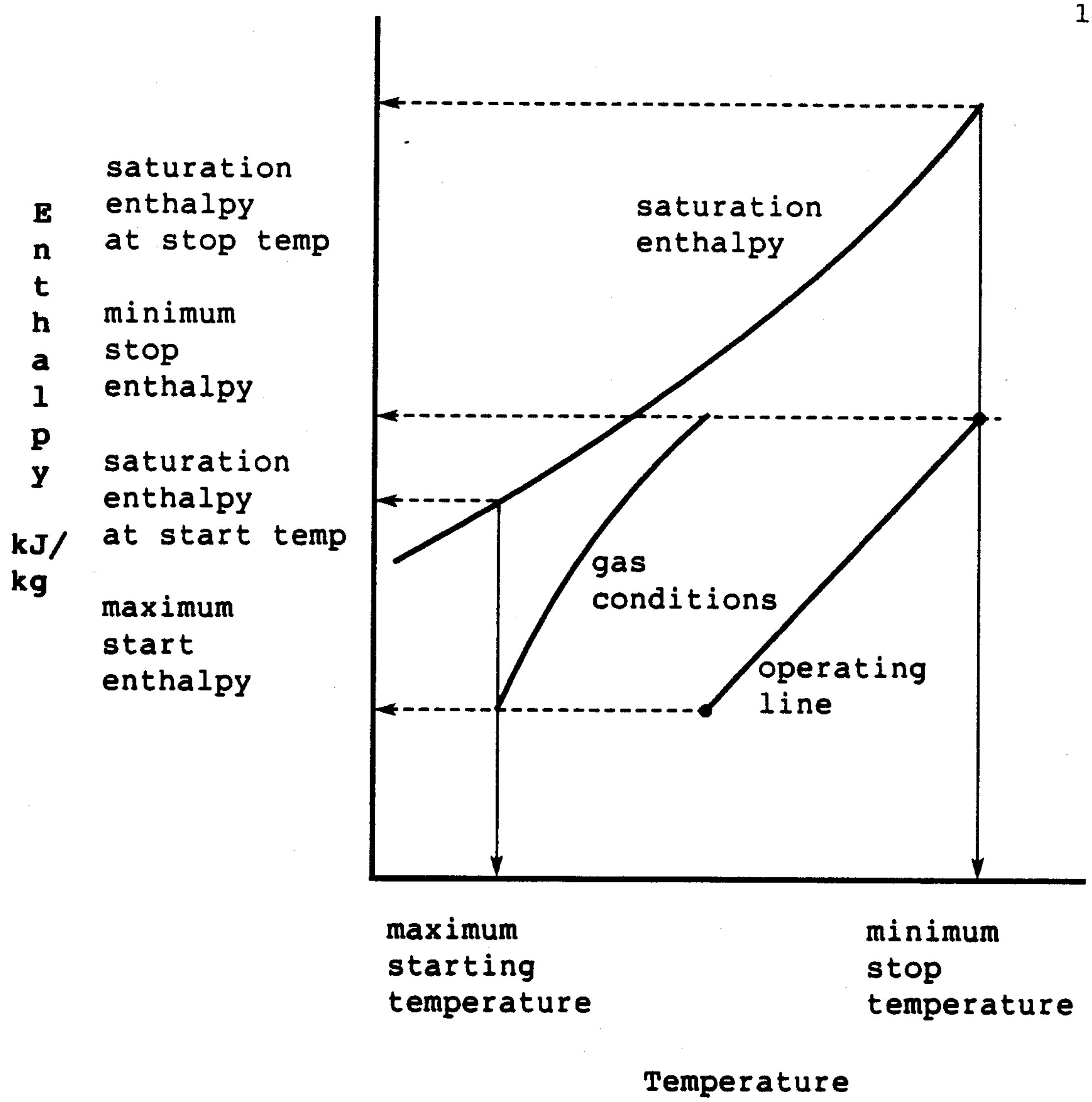


Figure A4. Plot routine schematic.

Examples

Note: Each of these runs illustrates a "perfect run", that is, all of the trial and error estimates to identify L'1 have already been accomplished.

<u>Example 1. Packed Column</u>

Inputs:

TL2 = 45.0
TL1 = 32.0
TG1 = 36.0
L'2 = 1.160
1st guess for L'1=1.136
G'1 = 0.987
Y'1 = 0.0182
Packing Choice : #5, 0.5 in. Berl Saddles
Delta Z = 0.05
Critical Humidity = 99
TI calculated
Shulman method, redone each time (choice #1)

<u>Comments</u>

1. The Shulman calculations typically predict differences in the energy transferred between the liquid and gas streams on the order of 5% to 7%. The overall mass transfer balance is always satisfied.

2. Notice that the mass and heat transfer coefficients are constant over the first increment of height. The coefficients are evaluated from the conditions at the bottom of an increment, but are printed once the conditions at the top of the increment have converged.

3. TI is always below TL, and the difference grows toward the top of the column. This is expected since the slope of the operating line is below that of the saturation line. When the slope of the operating line is greater than the slope of the saturation line, the difference between TI and TL decreases moving up through the column.

MASS AND HEAT TRANSFER COEFFICIENT CALCULATIONS

Primary Reference : Shulman et al, "Performance of Packed Columns", series of 5 articles, AIChE Journal, 1959 5(3) p. 290-294 (last article)

Adapted By: Treybal, Robert E. Mass Transfer Operations, 3rd Edition, 1980 p. 196-209

SYMBOL	UNITS	DEFINITION
Phi	Dimensionless	Holdup -- represents volume liquid/volume packed column
Ds	meters	Diameter of an equivalent sphere
Beta	Dimensionless	Exponent Used in holdup calculations
E	Dimensionless	Epsilon, dry bed voidage
a	m2/m3	interfacial area
jd	Dimensionless	j factor for mass transfer
jh	Dimensionless	j factor for heat transfer
kY	W/m2-K-Delta Y'	mass transfer coefficient
hg,hl	W/m2-K	gas, liquid heat transfer coefficient
Pr	Dimensionless	Prandtl number
Cp	N-m/Kg-K	thermal heat capacity
Nu	Dimensionless	Nusselt Number
kthl	W/m-K	liquid thermal conductivity
mu	Kg/m-sec	viscosity
Sc	Dimensionless	Schmidt Number
m,n,p	Dimensionless	exponents used in interfacial area calculations
Rhog	Kg/m3	gas phase density

SUBSCRIPT	REFERS TO
Lo	operating or moving liquid
Ls	static liquid
Lt	total liquid
W	water
A	absorption
V	vaporization
l	liquid
g	gas

VARIABLES AND OPERATIONAL PARAMETERS

VARIABLE	VALUE	VARIABLE	VALUE
Packing Choice	BERL SADDLES	Prg	.70
Nominal Size (mm)	13	Prl	5.15
L Prime	1.14	Scg	.60
G Prime	.99	Cpg	1004.1
G (G Prime/28.97)	.0341	mug	.187048E-04
Liquid Temp	32.00	mul	.766229E-03
Interface Temp	31.50	kthl	.622201E+00
Gas Temp	36.00	Rhog	1.152
Film Temp	33.75		

Note: all gas phase variables are evaluated at the film temperature -- T Film = (TG + TI)/2.0

Figure A5. Packed column design calculations.

```
HOLDUP CALCULATIONS
====== ============

Treybal, Table 6.5, p. 206

Epsilon  =     .630
L Prime  =    1.14  Kg/m2-sec
DS       =     .3162 meters
Beta     =     .9781

Phi-LsW  =     .0003
Phi-LtW  =     .0168
Phi-LoW  = (Phi-LtW) - (Phi-LsW)
         =     .01649


MASS TRANSFER EQUATIONS
==== ======== =========

LIQUID PHASE (Used to determine hl)
------ -----

     (      (Ds*L')        )
 Nu = (25.1*(-----)**0.45)*(Prl**0.45)
     (      ( mul )        )

GAS PHASE
--- -----
          (Ds*G Prime )
 jd = 1.195*(-----------)**(-0.36)
          (mug*(1-ELo))


     jd =  kY*Scg**(2/3)
           ------------
                G


HEAT TRANSFER EQUATIONS
==== ======== =========

CHILTON COLBURN ANALOGY:
------- ------- --------

                    hg
     jd = jh =    ----- *Prg**(2/3)
                   Cp*G'

LEWIS RELATION:
----- ---------

      hg
     ---- = 950 W-m/Kg-K
      kY
```

```
INTERFACIAL AREA CALCULATIONS
=========== ==== ============

Treybal, Table 6.4, p. 205


L Prime =  1.14 Kg/m2-sec
  m      = 16.28
  n      =   .0529
  p      =   .761

aAW = (m*(808*G'/Rhog**0.5)**n)*L'**p
    = 25.47 m2/m3


aVW = 0.85*aAW*(Phi-LtW/Phi-LoW)
    = 22.04 m2/m3


EQUATIONS EVALUATED
========= =========

Epsilon  =   .630

ELo = E - (Phi-LtW)
    =      .613

jd  =     .02567

kY  =      .03559  Kg/m2-sec-Delta Y'

Nu  =     906.77

hg, Chilton Colburn
    =     32.1  W/m2-K

hg, Lewis
    =     33.8  W/m2-K

hl, from Nu = hl*Ds/kthl
    =    1784.2 W/m2-K

Corresponding Volumetric Coefficients
============= ========== ============

kYaVW =    .7844 Kg/m3-sec-Delta Y'
hgaVW (CC) =     708.6   W/m3-K
hlaVW      =   39328.9   W/m3-K
hgaVW (Lewis) =     745.2  W/m3-K
```

Figure A5, continued.

PACKED COLUMN/COOLING TOWER DESIGN

INTEGRATION NUMBER 1

```
TL2 =  45.00                    TG2  unknown          VARIABLE      UNITS
L'2 =   1.160   ====>X  X====>  Y'2  unknown          ----------------------
                     X  X                             TEMPERATURES  DEGREES C
                     X  X                             FLOW RATES    kg/m2-sec
                  XXXXXXXXX
        Z PLUS    X   2.   X
       DELTA Z ----X--------X----
                  X        X    DELTA Z =  .050 meters
             Z ----X--------X----
                  X        X                          DESIGN PARAMETERS
                  X   1.   X                          ------------------------------------------
                  XXXXXXXXX
                     X  X                             CRITICAL RELATIVE HUMIDITY  =  100.0
TL1 =  32.00         X  X       TG1  =  36.00         L/G RATIO =  1.18
L'1   unknown   <====X  X<====  Y'1  =    .0182
                                G'1  =  .987          PRESSURE DROP  =  530.0 (N/m2) per m packing
                                G'S  =  .969          FLOOD POINT    = 2042.0(N/m2) per m of packing
```

GAS STREAM MASS TRANSFER			PROCESS ENERGY AND MASS DATA			TEMPERATURES IN DEGREES CENTIGRADE				HEAT AND MASS TRANSFER COEFFICIENTS		
SATURATION HUMIDITY (kg/kg)	BULK GAS HUMIDITY (kg/kg)	RELATIVE HUMIDITY (%)	BULK GAS ENTHALPY (kJ/kg)	LIQUID RATE (kg/m2s)	GAS RATE (kg/m2s)	LIQUID (C)	INTERFACE (C)	BULK GAS (C)	HEIGHT (m)	GAS hga (W/m3sK)	LIQUID hla (W/m3sK)	MASS kYa (kg/m3s)
.029721	.018200	48.5	82.9	1.1370	.9870	32.00	31.50	36.00	.000	708.6	39328.9	.78443
.030082	.018664	50.1	84.0	1.1374	.9866	32.21	31.71	35.85	.050	708.6	39328.9	.78443
.030448	.019124	51.7	85.0	1.1379	.9870	32.41	31.91	35.71	.100	709.1	39349.4	.78492
.030820	.019581	53.3	86.0	1.1383	.9875	32.62	32.12	35.58	.150	709.5	39369.8	.78541
.031197	.020035	54.8	87.1	1.1388	.9879	32.83	32.32	35.46	.200	710.0	39390.0	.78590
.031581	.020487	56.3	88.1	1.1392	.9883	33.04	32.53	35.36	.250	710.5	39410.1	.78638
.031971	.020936	57.8	89.2	1.1397	.9888	33.25	32.74	35.27	.300	711.0	39430.1	.78687
.032368	.021383	59.3	90.3	1.1401	.9892	33.46	32.94	35.18	.350	711.4	39450.1	.78736
.032773	.021829	60.7	91.3	1.1405	.9897	33.67	33.15	35.11	.400	711.9	39469.9	.78784
.033184	.022273	62.2	92.4	1.1409	.9901	33.89	33.37	35.04	.450	712.4	39489.8	.78833
.033604	.022716	63.5	93.5	1.1414	.9905	34.11	33.58	34.99	.500	712.9	39509.6	.78882
.034032	.023159	64.9	94.6	1.1418	.9909	34.33	33.79	34.95	.550	713.4	39529.3	.78931
.034468	.023602	66.2	95.7	1.1422	.9914	34.55	34.01	34.91	.600	713.9	39549.1	.78979
.034913	.024045	67.5	96.8	1.1427	.9918	34.77	34.23	34.88	.650	714.4	39568.9	.79029
.035368	.024489	68.8	97.9	1.1431	.9922	35.00	34.45	34.86	.700	714.9	39588.7	.79078
.035833	.024933	70.0	99.0	1.1435	.9927	35.23	34.67	34.85	.750	715.4	39608.6	.79127
.036309	.025379	71.2	100.2	1.1440	.9931	35.46	34.90	34.85	.800	715.9	39628.5	.79177
.036795	.025826	72.4	101.3	1.1444	.9935	35.69	35.12	34.86	.850	716.4	39648.4	.79227
.037293	.026276	73.6	102.5	1.1448	.9940	35.93	35.35	34.87	.900	717.0	39668.5	.79278
.037804	.026728	74.7	103.7	1.1453	.9944	36.17	35.59	34.89	.950	717.5	39688.7	.79329
.038327	.027183	75.8	104.9	1.1457	.9948	36.41	35.82	34.92	1.000	718.0	39709.0	.79380
.038864	.027641	76.9	106.1	1.1462	.9953	36.66	36.06	34.95	1.050	718.6	39729.4	.79432
.039415	.028103	77.9	107.3	1.1466	.9957	36.91	36.30	35.00	1.100	719.1	39750.0	.79484
.039982	.028569	79.0	108.6	1.1471	.9961	37.17	36.55	35.05	1.150	719.7	39770.8	.79537
.040564	.029040	79.9	109.8	1.1475	.9966	37.43	36.80	35.10	1.200	720.3	39791.8	.79591
.041163	.029516	80.9	111.1	1.1480	.9970	37.69	37.05	35.16	1.250	720.9	39812.9	.79645
.041781	.029997	81.9	112.4	1.1484	.9975	37.96	37.31	35.23	1.300	721.5	39834.4	.79700

Figure A6. Packed column design output.

.042417	.030485	82.8	113.8	1.1489	.9980	38.23	37.57	35.31	1.350	722.1	39856.0	.79756
.043073	.030980	83.7	115.1	1.1494	.9984	38.51	37.83	35.39	1.400	722.7	39878.0	.79812
.043751	.031482	84.6	116.5	1.1499	.9989	38.79	38.10	35.48	1.450	723.3	39900.2	.79870
.044451	.031991	85.4	117.9	1.1504	.9994	39.08	38.38	35.58	1.500	724.0	39922.8	.79928
.045176	.032510	86.2	119.4	1.1509	.9999	39.37	38.66	35.68	1.550	724.6	39945.8	.79988
.045926	.033037	87.1	120.8	1.1514	1.0004	39.67	38.94	35.78	1.600	725.3	39969.1	.80048
.046703	.033575	87.8	122.3	1.1519	1.0009	39.98	39.23	35.90	1.650	726.0	39992.8	.80110
.047510	.034123	88.6	123.9	1.1524	1.0014	40.30	39.53	36.02	1.700	726.7	40017.0	.80173
.048347	.034683	89.4	125.5	1.1530	1.0019	40.62	39.83	36.15	1.750	727.4	40041.6	.80237
.049218	.035255	90.1	127.1	1.1535	1.0024	40.95	40.14	36.28	1.800	728.1	40066.8	.80303
.050125	.035840	90.8	128.7	1.1541	1.0030	41.29	40.46	36.42	1.850	728.9	40092.5	.80370
.051070	.036440	91.5	130.4	1.1547	1.0035	41.63	40.79	36.56	1.900	729.6	40118.8	.80439
.052056	.037056	92.2	132.2	1.1553	1.0041	41.99	41.12	36.71	1.950	730.4	40145.7	.80510
.053087	.037687	92.9	134.0	1.1559	1.0047	42.36	41.46	36.87	2.000	731.3	40173.3	.80582
.054165	.038337	93.6	135.8	1.1565	1.0053	42.74	41.81	37.04	2.050	732.1	40201.6	.80657
.055295	.039006	94.2	137.7	1.1572	1.0059	43.13	42.18	37.21	2.100	732.9	40230.6	.80734
.056482	.039695	94.9	139.7	1.1578	1.0065	43.53	42.55	37.38	2.150	733.8	40260.5	.80813
.057728	.040407	95.5	141.7	1.1585	1.0071	43.94	42.93	37.57	2.200	734.7	40291.3	.80894
.059041	.041142	96.1	143.8	1.1592	1.0078	44.37	43.32	37.76	2.250	735.7	40323.1	.80979
.060426	.041904	96.8	146.0	1.1600	1.0085	44.82	43.73	37.96	2.300	736.7	40355.9	.81066
.060997	.042214	97.0	146.9	1.1603	1.0097	45.00	43.90	38.04	2.320	737.7	40389.8	.81156

INTEGRATION NUMBER 1 COMPLETE

MASS BALANCE: L'2 - L'1 = G's*(Y'2 - Y'1)
---- -------

LIQUID LOSS = .02328 kg/m2-sec

VAPOR GAIN = .02328 kg/m2-sec

ENERGY BALANCE: L'2*Hal2 - L'1*Hal1 = G's*(H'2 - H'1)
------ -------

ENERGY LOST BY LIQUID = 66.1315 kJ/m2-sec

ENERGY GAINED BY GAS = 61.9826 kJ/m2-sec

PERCENT DIFFERENCE BASED ON LIQUID = 6.3 %

NEW L PRIME 1 = 1.1367219 DIF = .00027812

NTG = 1.8966

Figure A6, continued.

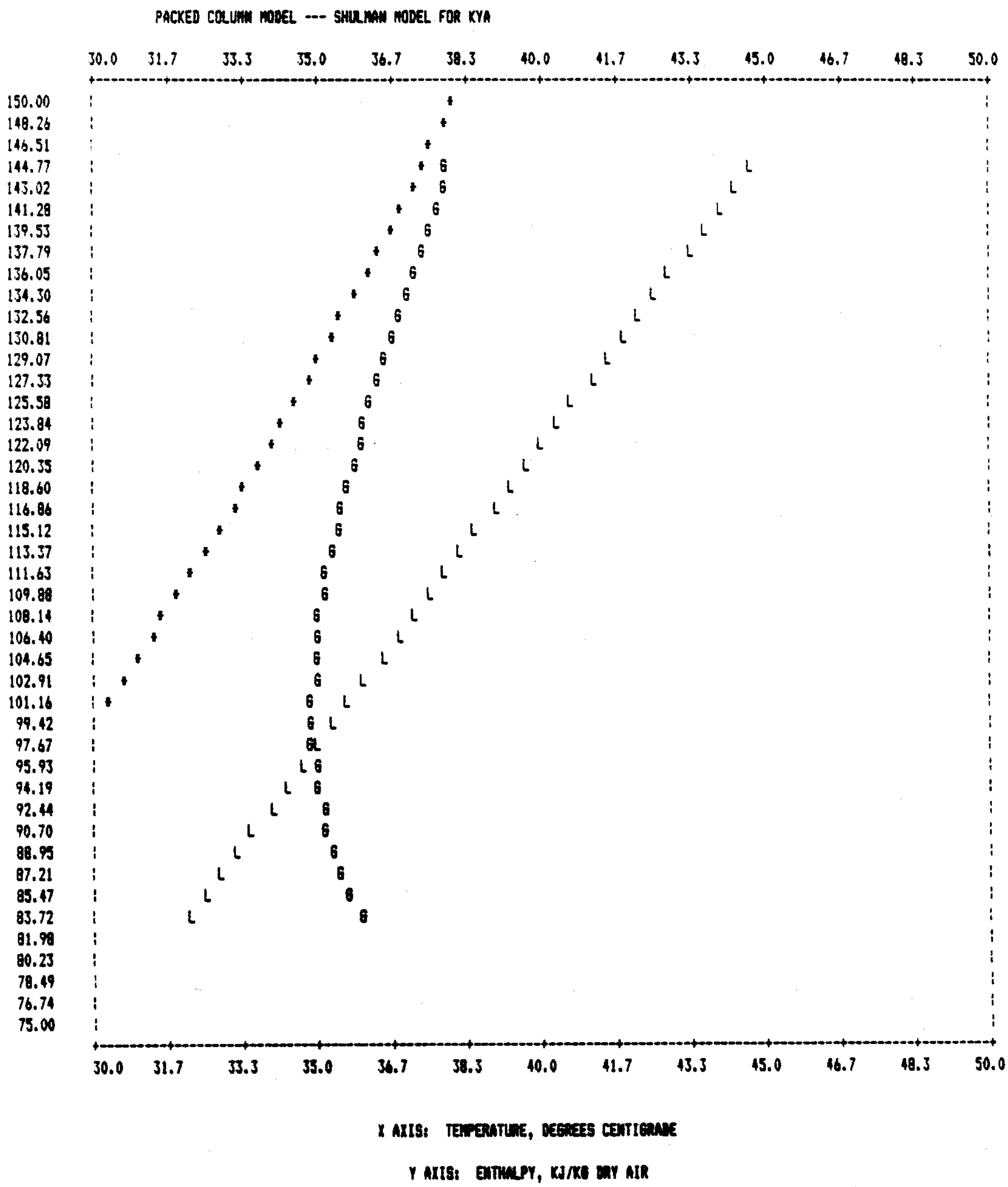


Figure A6, continued.

Example 2. Cooling Tower

This example is a slight modification of a performance simulation for a Union Carbide nuclear power plant cooling tower in Paducah, Kentucky published in an article entitled "Performance of Counterflow Cooling Tower Cells", by R. B. Wrinkle, AICHE Technical Manual, 1972, p. 118-121.

Inputs:

TL2 = 61.43
TL1 = 32.21
TG1 = 36.00
L'2 = 2.19
1st guess for L'1 = 2.09
G'1 = 5.475
Y'1 = 0.0182
Delta Z = 0.25 m
Critical Humidity = 99
TI = TL
kY'a = 0.252; use hga from Chilton Colburn

Comments

1. When TI = Tl, both overall mass and energy balances are always satisfied.

2. No pressure drop or flood point information is available for cooling towers.

PACKED COLUMN/COOLING TOWER DESIGN

INTEGRATION NUMBER 1

MECHANICAL DRAFT COOLING TOWER EXAMPLE

```
TL2 =  61.43                  TG2  unknown          VARIABLE      UNITS
L'2 =   2.190   ====>X  X====> Y'2  unknown          ----------------------
                     X  X                            TEMPERATURES  DEGREES C
                     X  X                            FLOW RATES    kg/m2-sec
                  XXXXXXXXXX
       Z PLUS     X   2.   X
     DELTA Z ----X--------X----
                  X        X    DELTA Z =  .250 meters
           Z ----X--------X----
                  X        X                         DESIGN PARAMETERS
                  X   1.   X                         ------------------------------------------
                  XXXXXXXXXX
                     X  X                            CRITICAL RELATIVE HUMIDITY  =  100.0
TL1 =  32.21         X  X     TG1  =  36.00          L/G RATIO =   .40
L'1   unknown   <====X  X<==== Y'1  =   .0182
                              G'1  =  5.475
                              G'S  =  5.377
```

GAS STREAM MASS TRANSFER			PROCESS ENERGY AND MASS DATA			TEMPERATURES IN DEGREES CENTIGRADE				HEAT AND MASS TRANSFER COEFFICIENTS		
SATURATION HUMIDITY (kg/kg)	BULK GAS HUMIDITY (kg/kg)	RELATIVE HUMIDITY (%)	BULK GAS ENTHALPY (kJ/kg)	LIQUID RATE (kg/m2s)	GAS RATE (kg/m2s)	LIQUID (C)	INTERFACE (C)	BULK GAS (C)	HEIGHT (m)	GAS hga (W/m3sK)	LIQUID hla (W/m3sK)	MASS kYa (kg/m3s)
.030992	.018200	48.5	82.9	2.0870	5.4750	32.21	32.21	36.00	.000	230.6	9263.1	.25200
.031366	.018351	49.0	83.3	2.0878	5.4742	32.41	32.41	35.96	.250	230.6	9263.1	.25200
.031754	.018505	49.5	83.6	2.0886	5.4750	32.62	32.62	35.93	.500	230.6	9263.1	.25200
.032158	.018662	50.0	84.0	2.0895	5.4758	32.83	32.83	35.89	.750	230.6	9263.1	.25200
.032578	.018821	50.5	84.4	2.0903	5.4766	33.05	33.05	35.86	1.000	230.6	9263.1	.25200
.033015	.018984	51.0	84.8	2.0912	5.4775	33.28	33.28	35.84	1.250	230.6	9263.1	.25200
.033470	.019150	51.5	85.2	2.0921	5.4783	33.51	33.51	35.81	1.500	230.6	9263.1	.25200
.033945	.019320	52.0	85.6	2.0930	5.4792	33.75	33.75	35.79	1.750	230.6	9263.1	.25200
.034440	.019493	52.5	86.0	2.0940	5.4801	34.00	34.00	35.77	2.000	230.6	9263.1	.25200
.034956	.019670	53.0	86.5	2.0949	5.4810	34.25	34.25	35.75	2.250	230.6	9263.1	.25200
.035496	.019851	53.5	86.9	2.0959	5.4819	34.51	34.51	35.74	2.500	230.6	9263.1	.25200
.036060	.020037	54.0	87.4	2.0969	5.4829	34.78	34.78	35.73	2.750	230.6	9263.1	.25200
.036651	.020227	54.6	87.9	2.0979	5.4839	35.06	35.06	35.72	3.000	230.6	9263.1	.25200
.037269	.020422	55.1	88.3	2.0989	5.4849	35.34	35.34	35.71	3.250	230.6	9263.1	.25200
.037918	.020622	55.6	88.9	2.1000	5.4859	35.64	35.64	35.71	3.500	230.6	9263.1	.25200
.038600	.020827	56.1	89.4	2.1011	5.4869	35.94	35.94	35.71	3.750	230.6	9263.1	.25200
.039316	.021038	56.7	89.9	2.1023	5.4880	36.26	36.26	35.72	4.000	230.6	9263.1	.25200
.040069	.021256	57.2	90.5	2.1034	5.4891	36.59	36.59	35.72	4.250	230.6	9263.1	.25200
.040863	.021480	57.8	91.1	2.1046	5.4902	36.92	36.92	35.73	4.500	230.6	9263.1	.25200
.041701	.021710	58.3	91.7	2.1059	5.4914	37.27	37.27	35.75	4.750	230.6	9263.1	.25200
.042586	.021948	58.9	92.3	2.1072	5.4926	37.63	37.63	35.77	5.000	230.6	9263.1	.25200
.043522	.022194	59.5	93.0	2.1085	5.4938	38.01	38.01	35.79	5.250	230.6	9263.1	.25200
.044514	.022448	60.0	93.7	2.1098	5.4951	38.40	38.40	35.81	5.500	230.6	9263.1	.25200
.045567	.022711	60.6	94.4	2.1113	5.4964	38.80	38.80	35.84	5.750	230.6	9263.1	.25200
.046686	.022984	61.2	95.1	2.1127	5.4978	39.23	39.23	35.87	6.000	230.6	9263.1	.25200
.047879	.023267	61.8	95.9	2.1142	5.4992	39.66	39.66	35.91	6.250	230.6	9263.1	.25200
.049151	.023561	62.4	96.7	2.1158	5.5007	40.12	40.12	35.95	6.500	230.6	9263.1	.25200

Figure A7. Mechanical draft tower output.

.051971	.024186	63.7	98.4	2.1192	5.5038	41.09	41.09	36.04	7.000	230.6	9263.1	.25200
.053538	.024519	64.3	99.3	2.1210	5.5054	41.61	41.61	36.10	7.250	230.6	9263.1	.25200
.055227	.024867	65.0	100.2	2.1228	5.5071	42.15	42.15	36.16	7.500	230.6	9263.1	.25200
.057051	.025231	65.7	101.2	2.1248	5.5089	42.72	42.72	36.22	7.750	230.6	9263.1	.25200
.059028	.025613	66.4	102.3	2.1269	5.5108	43.32	43.32	36.29	8.000	230.6	9263.1	.25200
.061177	.026015	67.1	103.4	2.1290	5.5127	43.95	43.95	36.36	8.250	230.6	9263.1	.25200
.063522	.026438	67.9	104.6	2.1313	5.5147	44.61	44.61	36.44	8.500	230.6	9263.1	.25200
.066091	.026885	68.7	105.8	2.1337	5.5169	45.31	45.31	36.53	8.750	230.6	9263.1	.25200
.068916	.027358	69.5	107.1	2.1362	5.5192	46.05	46.05	36.62	9.000	230.6	9263.1	.25200
.072040	.027860	70.3	108.5	2.1389	5.5215	46.83	46.83	36.72	9.250	230.6	9263.1	.25200
.075511	.028395	71.2	110.0	2.1418	5.5241	47.66	47.66	36.83	9.500	230.6	9263.1	.25200
.079392	.028967	72.1	111.6	2.1449	5.5267	48.54	48.54	36.94	9.750	230.6	9263.1	.25200
.083759	.029579	73.1	113.3	2.1482	5.5296	49.49	49.49	37.06	10.000	230.6	9263.1	.25200
.088711	.030239	74.1	115.1	2.1517	5.5326	50.51	50.51	37.19	10.250	230.6	9263.1	.25200
.094377	.030953	75.2	117.1	2.1556	5.5359	51.60	51.60	37.33	10.500	230.6	9263.1	.25200
.100923	.031730	76.4	119.3	2.1598	5.5394	52.79	52.79	37.48	10.750	230.6	9263.1	.25200
.108576	.032581	77.6	121.7	2.1643	5.5432	54.08	54.08	37.64	11.000	230.6	9263.1	.25200
.117650	.033519	79.0	124.3	2.1694	5.5473	55.50	55.50	37.81	11.250	230.6	9263.1	.25200
.128593	.034563	80.5	127.1	2.1750	5.5518	57.06	57.06	38.00	11.500	230.6	9263.1	.25200
.142070	.035736	82.2	130.4	2.1813	5.5567	58.80	58.80	38.19	11.750	230.6	9263.1	.25200
.159115	.037074	84.2	134.0	2.1885	5.5621	60.77	60.77	38.41	12.000	230.6	9263.1	.25200
.165283	.037526	84.8	135.3	2.1909	5.5741	61.43	61.43	38.48	12.073	230.6	9263.1	.25200

```
INTEGRATION NUMBER  1 COMPLETE

      MASS BALANCE:  L`2 - L`1 = G`s*(Y`2 - Y`1)
      ---- -------

                   LIQUID LOSS =   .10392 kg/m2-sec

                   VAPOR GAIN  =   .10392 kg/m2-sec

      ENERGY BALANCE:  L`2*Hal2 - L`1*Hal1 = G`s*(H`2 - H`1)
      ------ -------

         ENERGY LOST BY LIQUID =     281.4539 kJ/m2-sec

         ENERGY GAINED BY GAS  =     281.4693 kJ/m2-sec

         PERCENT DIFFERENCE BASED ON LIQUID  =    .0 %

         NEW L PRIME 1 = 2.0860841          DIF =   .00091593

         NTG =   .5624
```

Figure A7, continued.

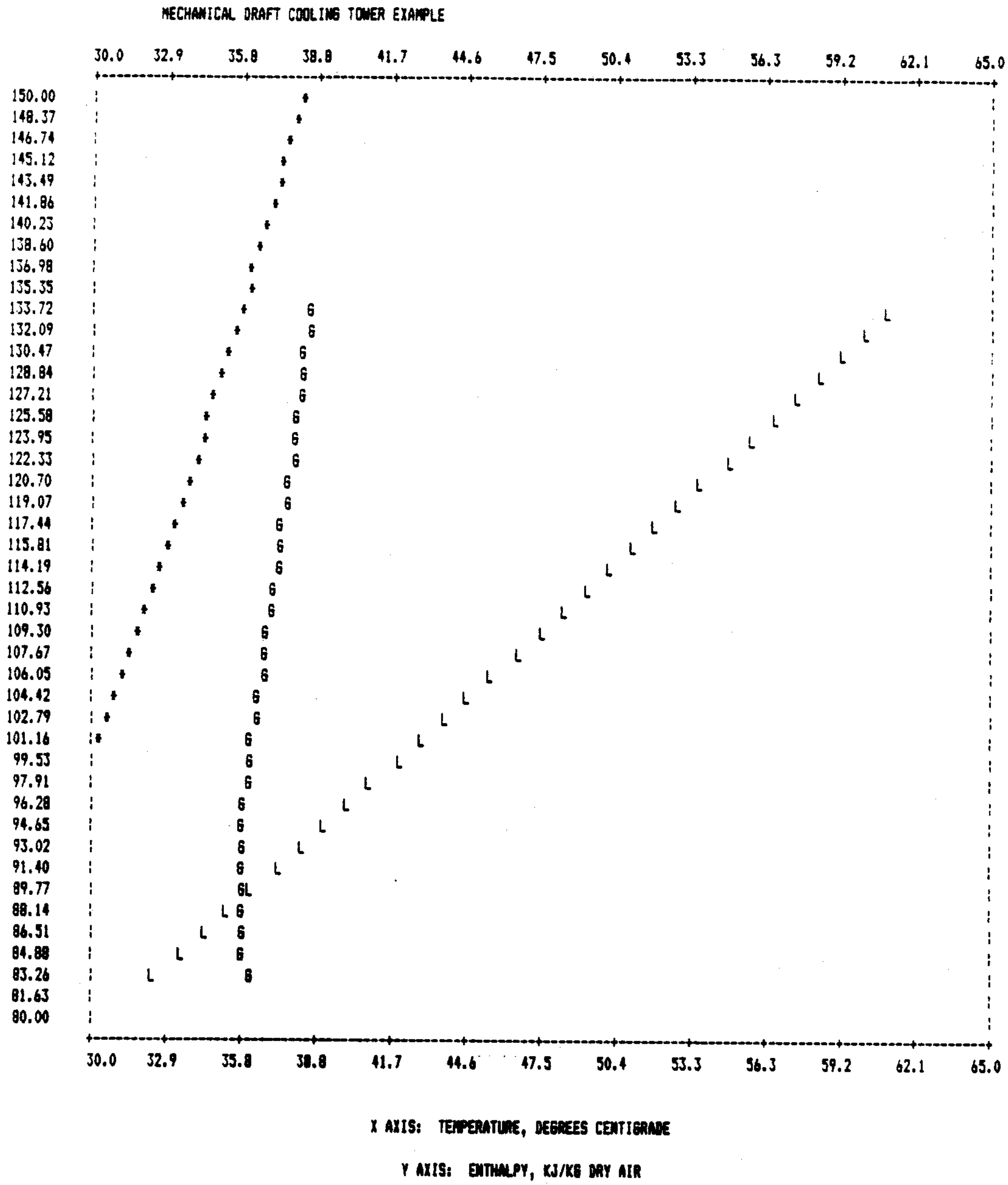


Figure A7, continued.

AUXILIARY DATA

1. Design Dry And Wet Bulb Temperature Geographical Table
2. Conversion Calculations For kY'a
3. Psychrometric Chart, SI units

1. Design Dry and Wet Bulb Geographical Table.

Table A2. Design Dry And Wet Bulb Temperature Geographical Table. Reference: McKelvey, K.K. and Brooke, M. The Industrial Cooling Tower, D.Van Nostrand Co. Inc., Princeton, N.J. 1959, 429p.

		Design Temperatures	
State	City	Dry Bulb	Wet Bulb
Alabama	Birmingham	95	79
	Mobile	95	80
	Montgomery	95	79
Arizona	Flagstaff	95	65
	Phoenix	108	78
	Tucson	105	73
	Yuma	110	79
Arkansas	Little Rock	97	80
California	Bakersfield	105	72
	El Centro	100	80
	Fresno	105	73
	Long Beach	92	72
	Los Angeles	92	72
	Needles	100	80
	Oakland	84	65
	Pasadena	92	72
	Sacramento	100	73
	San Bernardino	100	73
	San Diego	82	72
	San Francisco	84	65
Colorado	Denver	93	65
Connecticut	Bridgeport	95	77
	Hartford	95	77
	New Haven	95	77
Delaware	Wilmington	95	80
D.C.	Washington	96	80
Florida	Jacksonville	95	80
	Miami	91	80
	Pensacola	95	80
	Tampa	95	80
Georgia	Atlanta	95	79
	Augusta	95	79
	Brunswick	95	80
	Columbus	95	79
	Savannah	95	80
Idaho	Boise	98	67
Illinois	Chicago	96	77
	Peoria	97	78

Table A2, continued.

State	City	Design Temperatures Dry Bulb	Wet Bulb
Indiana	Evansville	96	78
	Fort Wayne	96	77
	Indianapolis	96	78
Iowa	Des Moines	95	78
	Sioux City	95	78
Kansas	Wichita	102	76
Kentucky	Louisville	98	80
Louisiana	New Orleans	93	81
	Shreveport	98	80
Maine	Augusta	88	73
	Bangor	88	73
	Portland	88	73
Maryland	Baltimore	97	80
	Cumberland	95	76
Massachusetts	Boston	90	75
	Fitchburg	92	75
	Springfield	92	75
	Worchester	92	75
Michigan	Detroit	93	75
	Flint	95	75
	Grand Rapids	95	76
	Saginaw	95	75
Minnesota	Duluth	93	74
	Minneapolis	95	76
	St. Paul	95	76
Mississippi	Vicksburg	98	80
Missouri	Kansas City	100	77
	St. Louis	100	77
Montana	Billings	92	66
	Helena	92	65
	Missoula	92	66
Nebraska	Lincoln	98	78
	Omaha	98	77
Nevada	Reno	96	65
New Hampshire	Concord	88	73
	Manchester	90	75
	Portsmouth	88	73
New Jersey	Camden	95	78
	Jersey City	92	77
	Newark	92	77
	Trenton	93	78
New Mexico	Albuquerque	96	70
	Santa Fe	95	65

Table A2, continued.

State	City	Design Temperatures Dry Bulb	Wet Bulb
New York	Albany	92	75
	Buffalo	92	75
	New York	93	77
	Rochester	92	75
	Syracuse	92	75
North Carolina	Asheville	90	75
	Charlotte	93	76
	Greensboro	93	76
	Raleigh	93	79
	Wilmington	93	80
North Dakota	Bismarck	95	73
Ohio	Akron	95	75
	Canton	95	75
	Cincinnati	96	78
	Cleveland	94	75
	Columbus	95	77
	Dayton	95	77
	Toledo	94	75
	Youngstown	95	75
Oklahoma	Oklahoma City	102	78
	Tulsa	102	78
Oregon	Baker	90	66
	Portland	90	68
	Roseburg	90	66
Pennsylvania	Altoona	90	75
	Erie	90	75
	Harrisburg	92	75
	Oil City	90	75
	Philadelphia	95	78
	Pittsburgh	95	75
	Scranton	90	75
Rhode Island	Pawtucket	90	75
	Providence	90	75
South Carolina	Charleston	93	80
	Columbia	93	76
	Greenville	93	75
South Dakota	Sioux Falls	98	75
Tennessee	Chatanooga	95	77
	Knoxville	93	77
	Memphis	98	80
	Nashville	95	79

Table A2, continued.

State	City	Design Temperatures Dry Bulb	Wet Bulb
Texas	Abilene	100	75
	Austin	98	79
	Corpus Christi	95	80
	Dallas	100	78
	El Paso	98	70
	Fort Worth	100	78
	Galveston	95	80
	Houston	95	80
	Lubbock	100	72
	San Antonio	98	79
	Port Arthur	95	80
	San Angelo	100	74
	Wichita Falls	100	76
Utah	Salt Lake City	97	66
Vermont	Burlington	88	73
	Rutland	88	73
Virginia	Norfolk	95	78
	Richmond	95	78
	Roanoke	95	76
Washington	Seattle	85	67
	Spokane	92	65
	Tacoma	85	66
	Walla Walla	90	66
	Wenatchee	90	66
	Yakima	90	66
West Virginia	Bluefield	95	75
	Charleston	95	75
	Huntington	95	77
	Parkersburg	95	76
	Wheeling	95	75
Wisconsin	Madison	95	75
	Milwaukee	95	75
Wyoming	Cheyenne	95	65

2. Conversion Calculations for $k_{Y'}a$

In English units, the tower characteristic is usually given in graphical form as a function of L'/G', and is defined as:

$$\text{Tower Characteristic} = \frac{KaV}{L'}$$

Where:

K = mass transfer coefficient, $lbm/hr\text{-}ft^2$
a = specific area, ft^2 of surface area per cubic foot of packing.
V = active tower volume, ft^3/ft^2 of plan area
L'= liquid mass flow rate, $lbm/hr\text{-}ft^2$

To determine kY'a for this program:

1. Calculate V:

$$V = \frac{\text{volume of packing}}{\text{cross sectional area of tower}}$$

2. Calculate L':

$$L' = \frac{\text{water loading, lbm/hr}}{\text{cross sectional area of tower}}$$

3. Alternatively, obtain V/L' directly as:

$$V/L' = \frac{\text{volume of packing}}{\text{cross sectional area of tower}}$$

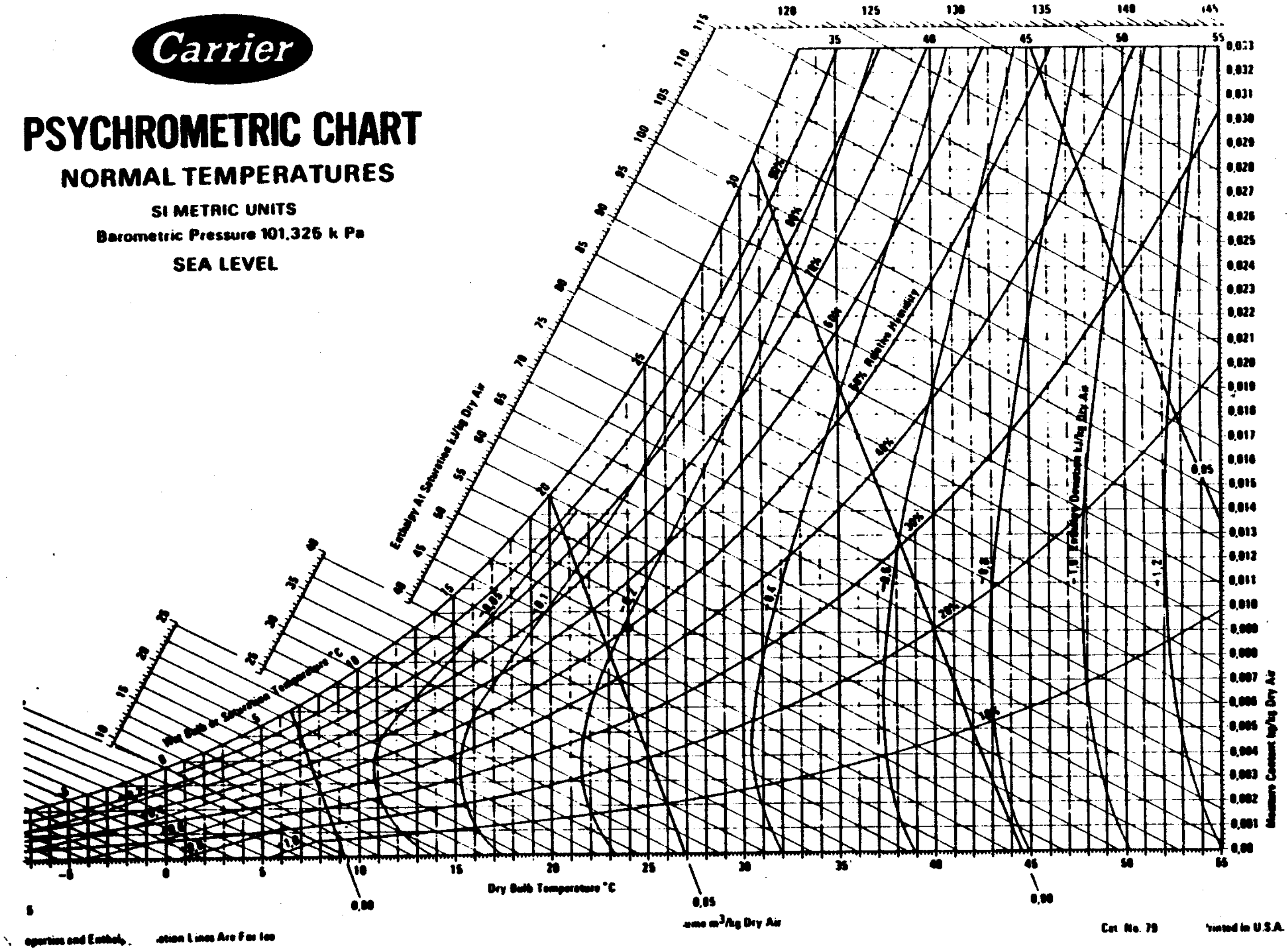
4. Calculate Ka:

$$Ka = \frac{KaV/L'}{V/L'} = \frac{\text{tower characteristic}}{V/L'}$$

5. Convert Ka to kY'a:

Ka, $lbm/hr\text{-}ft^3$ * (3.281)**3/(2.2*3600) = kY'a

Ka, english * 0.00445 = kY'a, $kg/m^3\text{-sec}$


Carrier
PSYCHROMETRIC CHART
NORMAL TEMPERATURES
SI METRIC UNITS
Barometric Pressure 101.325 k Pa
SEA LEVEL
Enthalpy At Saturation kJ/kg Dry Air
Wet Bulb or Saturation Temperature °C
Relative Humidity
Enthalpy Deviation kJ/kg Dry Air
Dry Bulb Temperature °C
m³/kg Dry Air
Moisture Content kg/kg Dry Air
Cat. No. 79
Printed in U.S.A.

APPENDIX A3. Program Information

This appendix provides details on the design program itself, including structure, syntax, compiler information, as well as a full program listing. Flow diagrams and the program listing are given in separate appendices due to their size.

A3.1. Program Organization

The FORTRAN compiler used to create the object and execution codes is published by Microsoft, Incorporated, for use on personal computers. The compiler is a two pass format followed by a linker to connect the object files into the final execution file. During program development the compile time became very long and stack overflow errors due to large variable lists were very frequent, so the source code was split into separate groups. Table 3 lists the FORTRAN files, the subroutines, and the functions used in the program.

As table 3 shows, the design program contains 1 main program, 21 subroutines, and 13 functions; the total program contains approximately 1900 lines of code, including comments.

In addition to the design program, there are several support routines, each of which is described as follows:

1. **HUMID.EXE** -- This is an execution file of a complied utility program written in BASIC to send a compressed print sequence to the printer to be used, then calls the main design program, DESIGN.EXE.

2. **DESIGN.EXE** -- This is the main design program, an execution file. The flow diagram in A3.2 applies to this file.

3. **PDROP.DAT** -- This is pressure drop data used in the Shulman packed column models.

4. **SAT.DAT** -- This is the saturation enthalpy line data.

5. **PROG.DAT** -- A file written by the design program as it integrates, used in the plot subroutine to show the gas and liquid conditions in the column. Erased and regenerated with each integration. This file will not show on the master disc until the design program has been run.

6. **NTG.DAT** -- A data file written by the design program as it integrates, used by the NTU integration routine to calculate NTU. Erased and regenerated with each integration, this file will not be seen on the system disc unless the user interrupts the program during execution.

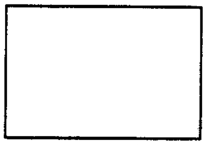
Table A3. Design program organization.

FORTRAN FILE NAME	SUBROUTINE OR FUNCTION	COMMENTS
FULL.FOR	Main Program	Title: Design
SUBS1.FOR	Menu1	Mass Trx. Models
	Menu2	Choose Trx. Coef.
	Menu3	Access Menu
	Header	Data Header Line
	Head1	Integration No.
	Diag	Tower Diagram
SUBS2.FOR	Inputs	Main Data Inputs
	Menu4	Integration Complete
	Sheg	Shulman Model
	Endint	Integration Summary
	Screen	Scrolls Screen
	Pageup	Set Page Up
	Titl	Interface Temp.
	Delp	Pressure Drop
	Char	Column Data
	Plot	Plot Subroutine
	Ovrall	Overall Balance
SUBS3.FOR	Trxcof	Transfer Coef.
	Relhum	Relative Humidity
	Shul	Calls Shulman Model
	Satf	Checks Saturation
FUNS.FOR	SCG(TF)	Schmidt, Gas
	DAB(TF)	Diffusivity, Gas
	RHOG(TF)	Density, Gas
	PRG(TF)	Prandtl, Gas
	CPG(TF)	Heat Capacity, Gas
	HPRIME(T,YPR)	Enthalpy, Gas
	RMUG(TF)	Viscosity, Gas
	PRL(TL)	Prandtl, Liquid
	RKTHG(TF)	Th. Cond., Gas
	RMUL(TL)	Viscosity, Liquid
	CS(T,Y)	Humid Heat, Gas
	YSATPR(TI,YPS,PSAT)	Sat'n Humidity, Gas

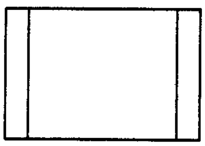
APPENDIX A3.2 Flow Diagram

Symbols Used in Flow Diagram

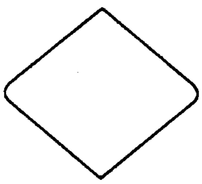
Terminus (Start or Stop)



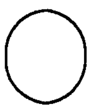
Process Calculations



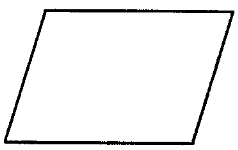
Subroutine



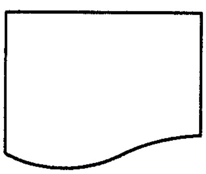
Decision



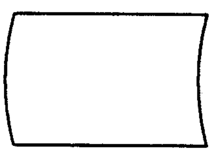
Connection, Entry, or Return Point



Input / Output

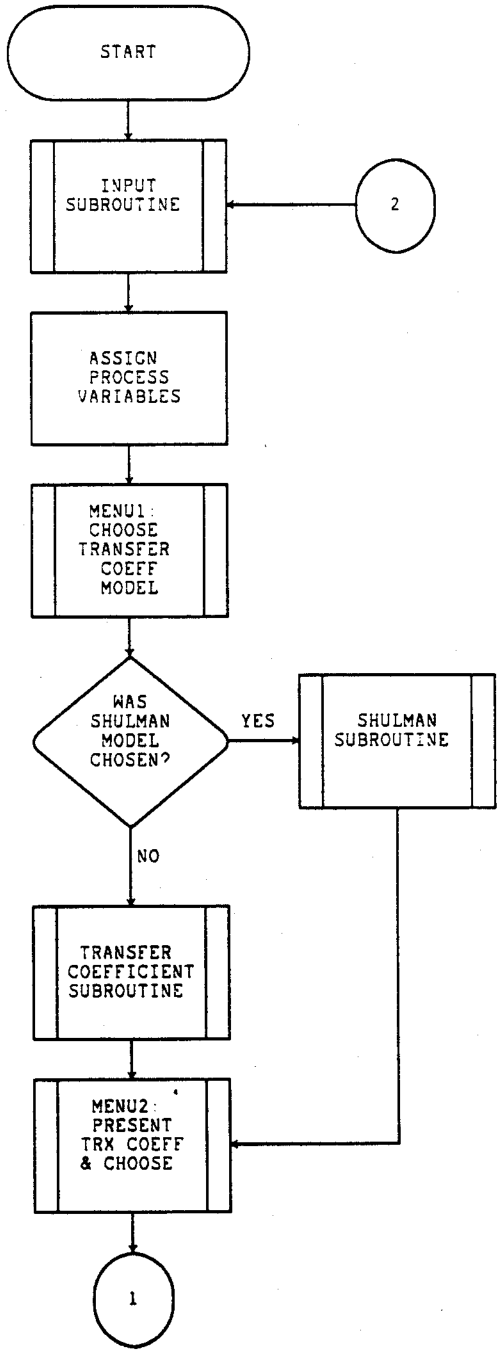


Printed Output

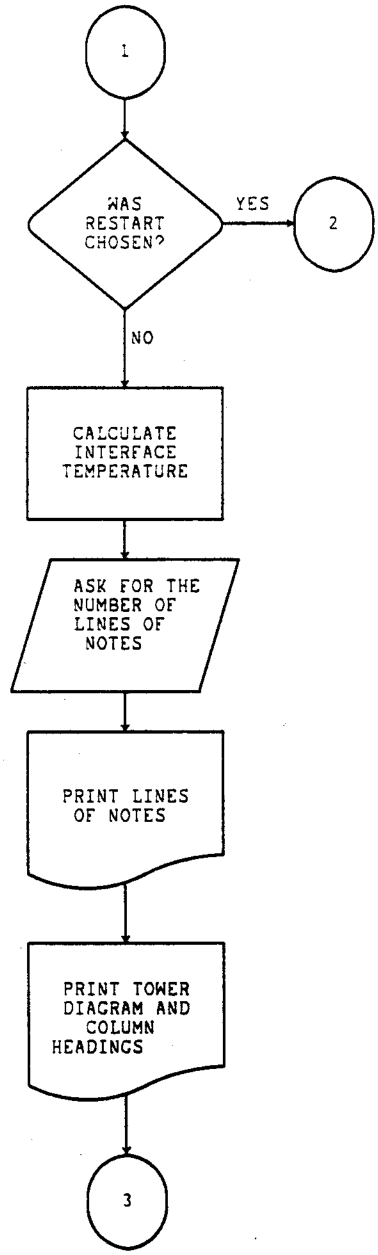


Write to Disk File

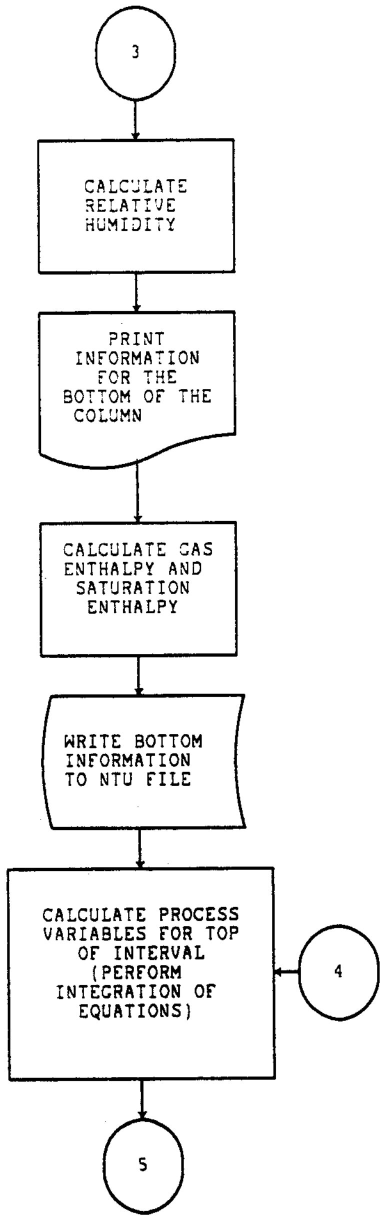
Flow Diagram For Program "Design"



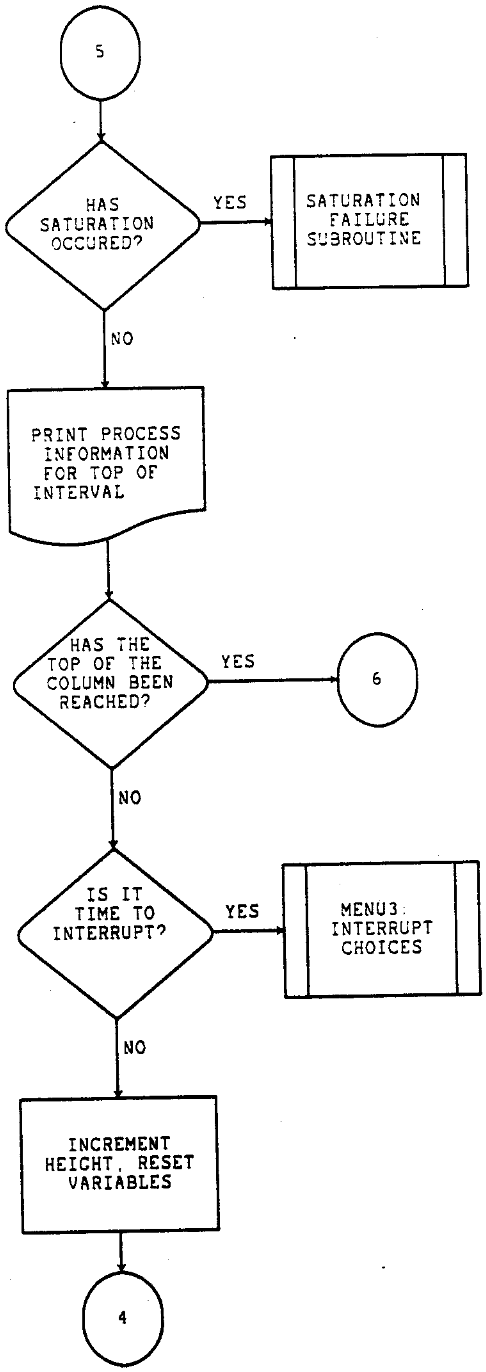
Flow diagram, continued



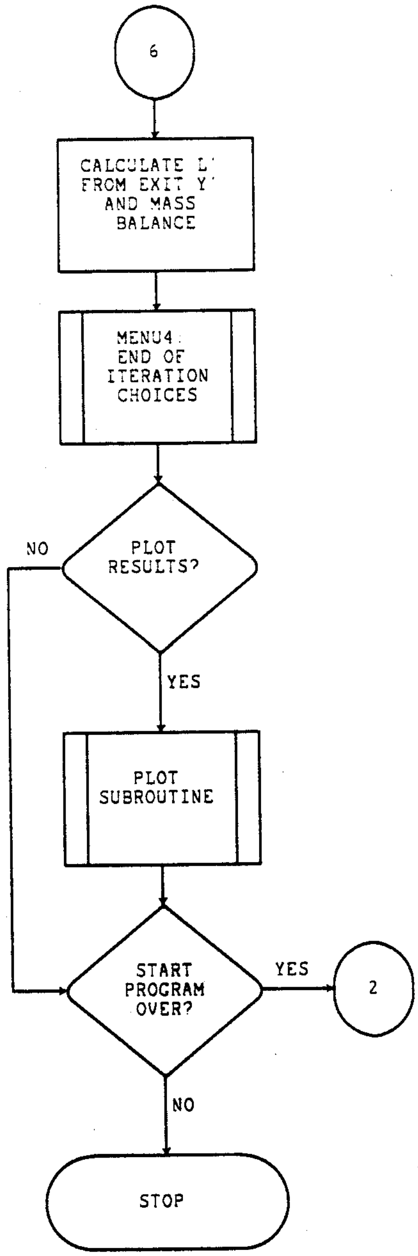
Flow diagram, continued



Flow diagram, continued



Flow diagram, continued



APPENDIX A3.3 Program Listing

APPENDIX A3.3 Table Of Contents

MAIN PROGRAM LISTING

```
      PROGRAM DESIGN
      IMPLICIT REAL*8 (A-H,O-Z)
      IMPLICIT INTEGER(I,J,M,N)
      IMPLICIT REAL*8 (K,L)
      CHARACTER MESS(10)*100
      INTEGER L1,TIC,SFC
      OPEN(5,FILE='LPT1:')
C
C      BEGIN DATA ENTRY AND INITIALIZATION AREA
C
  12  CALL INPUTS(TL2,TL1,TG1,LPR2,GPR1,YPR1,
     &LFACT,DELZ,CRTHUM,NTERUP,TIC)
C
C      OBTAIN A HEAT TRANSFER RATIO FOR THE
C      NON SHULMAN CALCULATIONS
C
      I=2
      M1C=1
      M2C=0
      TI=TL2
      CALL TRXCOF(I,M1C,M2C,TI,TG1,TL2,HGA,HLA,KPYA,
     &LPR2,GPR1,YPR1,CF,FD)
      HTRAT=HLA/HGA
      DELZP=DELZ
      NNTERUP=NTERUP
C
C
C
C
C      ASSIGN PROCESS VARIABLES INITIAL VALUES
C      THIS IS ALSO THE RETURN POINT FOR
C      INTERRUPTION DURING EXECUTION AND FOR
C      SATURATION FAILURE.
C
  15  TL=TL1
      TG=TG1
      DELZ=DELZP
      Z=0
      M1C=0
      M2C=0
      INTCNT=0
      IWIN=0
      YPR=YPR1
      LPR=LPR2*(1.-LFACT)
      LPR1=LPR
      GPR=GPR1
      GPRS=GPR/(1.0+YPR)
      OPEN(10,FILE='PROG.DAT',STATUS='NEW')
```

```
C
C      BEGIN TRANSFER COEFFICIENT CALCULATIONS
C      MENU1 SHOWS THE CHOICES OF CALCUATIONS
C
  20   CALL MENU1(M1C,GPRS,LPR)
      IF(M1C.LT.3)THEN
        CALL SHUL(I,M1C,M2C,TI,TG,TL,HGA,HLA,KPYA,
     &  LPR,GPR,YPR,TIC,ANS,IER)
        KPYA1=KPYA
        GO TO 39
      ELSE
        CALL TRXCOF(I,M1C,M2C,TI,TG,TL,HGA,HLA,KPYA,
     &  LPR,GPR,YPR,CF,FD)
      ENDIF
C
C      NOW PRESENT COEFFICIENTS AND ASK FOR A CHOICE
C
      IF(M1C.GT.2)THEN
      CALL MENU2(M2C,TG,TI,YPR,HTRAT,HGA,HLA,KPYA)
      IF(M2C.EQ.6)GO TO 15
      SLOPE=0.-(HLA/(KPYA*1000.))
      KPYA1=KPYA
C
C     WHEN TIC EQUALS 1 THEN WE ARE CALCULATING TI
C
      IF(TIC.EQ.1)THEN
        CALL TITL(TL,TG,TI,YPR,SLOPE)
      ELSE
        TI=TL
      ENDIF
      ENDIF
C
C      NOW ADD THE NOTES TO BE PRINTED
C
  39  CALL SCREEN(20)
      WRITE(*,*)'     ENTER THE NUMBER OF LINES OF'
      WRITE(*,*)'     NOTES TO BE WRITTEN -- UP TO 9'
      WRITE(*,*)'     '
      WRITE(*,*)'     THEN PRESS RETURN'
      CALL SCREEN(5)
      READ(*,*)NL
      IF(NL.EQ.0)THEN
        CALL PAGEUP()
        CALL HEADL(INTCNT)
        GO TO 41
      ENDIF
      DO 10 INL=1,NL
      WRITE(*,97)INL
      WRITE(*,*)'     '
      IF(INL.EQ.1)WRITE(*,98)
      WRITE(*,*)'    '
      READ(*,*)MESS(INL)
```

```
10   CONTINUE
```

```
C
C     PAGEUP SETS THE PRINTER TO THE TOP OF A PAGE,
C     THEN THE ITERATION COUNTER, THEN THE MESSAGE,
C     THE TOWER DIAGRAM, AND THE COLUMN HEADERS
      CALL PAGEUP()
      CALL HEADL(INTCNT)
      DO 16 INL=1,NL
   16 WRITE(5,99)MESS(INL)
   97 FORMAT(6X,'ENTER NOTE #',I2,' ENCLOSED IN ',
     &'APOSTROPHE MARKS')
   98 FORMAT(6X,'''THIS IS AN EXAMPLE OF A NOTE''')
   99 FORMAT(5X,A101)
C
C
C      PRINT THE TOWER DIAGRAM
C
   41 IF(INTCNT.EQ.0)THEN
        CALL CHAR(I,DS,M,N,P,EPSI,LPR,GPR,YPR,CF,FD)
      CALL DIAG(TL2-273.15,TL1-273.15,LPR2,DELZ,
     &TG1-273.15,YPR1,GPR1,GPRS,CRTHUM,M1C,ANS,FD,IER)
      ENDIF
C
C      NOW PRINT THE HEADINGS FOR THE MAIN BODY
C
   40 CALL HEADER()
C
C      NOW CALCULATE THE BOTTOM RELATIVE HUMIDITY
C      AND THEN PRINT THE INITIAL SET OF INFORMATION.
C
      CALL RELHUM(TG,YPR,RH)
      HDUM=HPRIME(TG-273.15,YPR)/1000.
      CALL YSATPR(TI,YPS,PSAT)
      WRITE(5,911)YPS,YPR,RH,HDUM,LPR,
     &GPR,+TL-273.15,+TI-273.15,+TG-273.15,
     &Z,HGA,HLA,KPYA
      HSTAR=HPRIME(TI-273.15,YPS)/1000.
      YVAL=1.0/(HSTAR-HDUM)
      OPEN(11,FILE='NTG.DAT',STATUS='NEW')
      WRITE(11,*)HDUM,YVAL
C
C     NOW WE ENTER THE MAIN LOOP TO SOLVE THE
C     DIFFERENCE EQUATIONS OVER THE HEIGHT INTERVAL
C
C     1.   CALCULATE THE AVERAGES USING BOTTOM VALUES
C
      GPRS=GPR/(1.0+YPR)
   45 IF(TIC.EQ.1)THEN
        SLOPE=0.-(HLA/(KPYA*1000.))
        CALL TITL(TL,TG,TI,YPR,SLOPE)
      ELSE
        TI=TL
      ENDIF
```

```
DELTIG=TI-TG
CALL YSATPR(TI,YPS,PSAT)
```

```
      YIPR=YPS
      DELYIG=YIPR-YPR
      DELTIL=TI-TL
      CSA=CS(TG,YPR)
      LPRA=LPR
      GPRA=GPR
C
C     2.  USE THE BOTTOM AVERAGES TO PREDICT VALUES AT THE C
     C          TOP OF THE INCREMENT
      DELYPR=(KPYA*DELYIG*DELZ)/GPRS
      YPRTOP=YPR+DELYPR
      DELTG=((HGA*DELTIG)/(GPRS*CSA))*DELZ
      TGTOP=TG+DELTG
      DELLPR=GPRS*DELYPR
      LPRTOP=LPR+DELLPR
      GPRTOP=GPR-DELLPR
      IF(TIC.EQ.0)THEN
        CALL OVRALL(LPRTOP,LPR,GPRS,YPRTOP,YPR,
     &  TGTOP,TG,TL,TLTOP,0)
      ELSE
       AL=(GPRS*DELTIL*DELYPR)/LPRA
       BL=(HLA*DELZ*DELTIL)/(LPRA*4178.)
       DELTL=AL-BL
       TLTOP=TL+DELTL
      ENDIF
      DO 50 L1=1,6
C
C     3.  CALCULATE A SET OF AVERAGES USING THE PREDICTED
C         TOP VALUES; REPEAT 6 TIMES
C
      IF(TIC.EQ.1)THEN
        SLOPE=0.-(HLA/(KPYA*1000.))
        CALL TITL(TLTOP,TGTOP,TITOP,YPRTOP,SLOPE)
      ELSE
        TITOP=TLTOP
      ENDIF
      CALL YSATPR(TITOP,YPS,PSAT)
      TYIPR=YPS
      TDLTIG=TITOP-TGTOP
      TDLYIG=TYIPR-YPRTOP
      TDLTIL=TITOP-TLTOP
      TCSA=CS(TGTOP,YPRTOP)
      TLPRA=LPRTOP
      TGPRA=GPRTOP
C
C     4.  CALCULATE A REAL SET OF AVERAGES
C
      TYIPR=(TYIPR+YIPR)/2.0
      TDLTIG=(TDLTIG+DELTIG)/2.0
      TDLYIG=(TDLYIG+DELYIG)/2.0
      TDLTIL=(TDLTIL+DELTIL)/2.0
      TCSA=(TCSA+CSA)/2.0
```

```
TLPRA=(TLPRA+LPRA)/2.0
TGPRA=(TGPRA+GPRA)/2.0
```

```
C
C      5.  RECALCULATE THE TOP VALUES USING THE TRUE
C          AVERAGES AND THE BOTTOM VALUES
C
C      (THESE ARE THE BEST PREDICTIONS)
C
      DELYPR=(KPYA*TDLYIG*DELZ)/GPRS
      YPRTP2=YPR+DELYPR
      DELTG=((HGA*TDLTIG)/(GPRS*TCSA))*DELZ
      TGTP2=TG+DELTG
      DELLPR=GPRS*DELYPR
      LPRTP2=LPR+DELLPR
      GPRTP2=GPR-DELLPR
      IF(TIC.EQ.0)THEN
        CALL OVRALL(LPRTP2,LPR,GPRS,YPRTP2,YPR,
     &  TGTP2,TG,TL,TLTP2,0)
      ELSE
        AL=(GPRS*TDLTIL*DELYPR)/TLPRA
        BL=(HLA*DELZ*TDLTIL)/(TLPRA*4178.)
        DELTL=AL-BL
        TLTP2=TL+DELTL
      ENDIF
        YPRTOP=YPRTP2
        TGTOP=TGTP2
        TLTOP=TLTP2
        LPRTOP=LPRTP2
        GPRTOP=GPRTP2
C
C       THIS IS THE TOP END OF THE LOOP THAT
C       IS REPEATED SIX TIMES
C
  50    CONTINUE
      TI=TITOP
      CALL RELHUM(TGTP2,YPRTP2,RH)
      IF(RH.GT.CRTHUM)THEN
        CALL SATF(SFC,GPR1)
        GOTO(15,12,90,15)SFC
      ENDIF
C
C
C      INCREMENT HEIGHT AND PRINT CONVERGENCE
C      VALUES.
C
        Z=Z+DELZ
      CALL YSATPR(TI,YPS,PSAT)
      HDUM=HPRIME(TGTP2-273.15,YPRTP2)/1000.
      IF (TLTP2.GE.TL2)THEN
        TF=DABS((TL2-TLL)/(TLTP2-TLL))
        TI=TIL+TF*(TI-TIL)
        CALL YSATPR(TI,YPS,PSAT)
        YPRTP2=YPRL+TF*(YPRTP2-YPRL)
        TGTP2=TGL+TF*(TGTP2-TGL)
```

```
CALL RELHUM(TGTP2,YPRTP2,RH)
HDUM=HPRIME(TGTP2-273.15,YPRTP2)/1000.
```

```
        LPRTP2=LPRL+TF*(LPRTP2-LPRL)
        GPRTP2=GPRL+TF*(GPRTP2-GPRL)
        TLTP2=TL2
        Z=ZL+TF*(Z-ZL)
      ENDIF
      WRITE(5,911)YPS,YPRTP2,RH,HDUM,
     &LPRTP2,GPRTP2,+TLTP2-273.15,+TI-273.15,
     &+TGTP2-273.15,Z,HGA,HLA,KPYA
 911  FORMAT(1X,F8.6,3X,F8.6,5X,F4.1,4X,F7.1,2(3X,F7.4),
     &3X,F5.2,5X,F5.2,4X,F5.2,2X,F6.3,2X,F8.1,2X,
     &F10.1,2X,F8.5)
      WRITE(10,*)+TG-273.15,+TL-273.15,
     &+HPRIME(TG-273.15,YPR)/1000.
      HSTAR=HPRIME(TI-273.15,YPS)/1000.
      YVAL=1.0/(HSTAR-HDUM)
      WRITE(11,*)HDUM,YVAL
C
C
C      TEST FOR THE TOP OF THE COLUMN,
C      AND RETURN IF NOT THERE
C
      IF(TL2.GT.TLTP2)THEN
        IWIN=IWIN+1
        IF(MOD(IWIN,NTERUP).EQ.0)THEN
          IWIN=0
          CALL MENU3(M3C,DELZ,CRTHUM,NTERUP)
          IF(M3C.EQ.5)THEN
            CLOSE(10,STATUS='DELETE')
            GO TO 12
          ELSEIF(M3C.EQ.1)THEN
            GO TO 90
          ENDIF
      ENDIF
C
C
  75    TL=TLTP2
        TG=TGTP2
        LPR=LPRTP2
        YPR=YPRTP2
        GPR=GPRS*(1.0+YPR)
        TLL=TLTP2
        TGL=TGTP2
        LPRL=LPRTP2
        YPRL=YPRTP2
        GPRL=GPRS*(1.0+YPRL)
        TIL=TI
        ZL=Z
        DELZ=DELZP
        NTERUP=NNTERUP
      CALL TRXCOF(I,M1C,M2C,TI,TG,TL,HGA,HLA,KPYA,
     &LPR,GPR,YPR,CF,FD)
        GO TO 45
```

```
C
C      ONCE AT THE TOP OF THE COLUMN,
C      CALCULATE A NEW L PRIME 2 AND COMPARE
C      TO THE PREVIOUS VALUE.
C
      ELSE
        CALL ENDINT(LPR1,LPRTP2,LPR2,YPR1,YPRTP2,GPRS,
     &  TG1,TGTP2,TL1,TLTP2,INTCNT,TIC)
        WRITE(5,*)'       '
      CALL MENU4(ICHO,M4C,LPRNEW)
      GOTO(90,15,12)M4C
      DL=LPRTP2-LPR2
      LPR1=LPR1-DL
      KPYA=KPYA1
        LPR=LPR1
        LFACT=1.-(LPR1/LPR2)
        INTCNT=INTCNT+1
        TL=TL1
        TI=TL
        TG=TG1
        GPR=GPR1
        YPR=YPR1
        Z=0
        IWIN=0
        ICHECK=0
      CALL PAGEUP ()
      CALL HEADL(INTCNT)
        GO TO 40
      ENDIF
 90   WRITE(5,*)'         '
      CLOSE (10)
      CALL PLOT()
      CALL SCREEN(40)
      WRITE(*,*)'       PRESS 1, THEN RETURN, TO START OVER'
      WRITE(*,*)'       PRESS ANY OTHER NUMBER TO STOP'
      CALL SCREEN(10)
      READ(*,*)ICHO
      IF(ICHO.EQ.1)GOTO 12
      STOP
      END
```

MENUS

```
C
C      THIS IS THE FIRST MENU -- CHOICES FOR TRXCOF
C
      SUBROUTINE MENU1(M1C,GS,LP)
      IMPLICIT REAL*8 (A-Z)
      INTEGER I,M1C,IC
      CHARACTER MESS(3)*18
      DO 10 IC=1,3
   10 MESS(IC)='** OUT OF RANGE **'
      IF((LP.GE.0.68).AND.(LP.LE.6.1))THEN
        MESS(1)='      IN RANGE      '
      ENDIF
      IF((LP.GE.1.2641).AND.(LP.LE.3.8194))THEN
        IF((GS.GT.1.3592).AND.(LP.LE.4.07763))THEN
          MESS(2)='      IN RANGE      '
        ENDIF
      ENDIF
      IF((LP.GE.0.47572).AND.(LP.LE.4.07763))THEN
        IF((GS.GT.0.90252).AND.(GS.LE.2.2835))THEN
          MESS(3)='      IN RANGE      '
        ENDIF
      ENDIF
      CALL SCREEN (21)
      WRITE(*,100)
  100 FORMAT(3X,'     ')
      WRITE(*,101)
  101 FORMAT(10X,'MENU ONE -- MASS TRANSFER MODELS')
      WRITE(*,100)
      WRITE(*,102)
  102 FORMAT(6X,'TYPE',11X,'APPLICATION',11X,'VALIDITY')
      WRITE(*,103)
  103 FORMAT(6X,12('-'),3X,14('-'),3X,18('-'))
      WRITE(*,104)MESS(1)
  104 FORMAT(6X,'SHULMAN',8X,'PACKED COLUMNS',3X,A18)
      WRITE(*,105)MESS(2)
  105 FORMAT(6X,'NORMAN',9X,'COOLING TOWERS',3X,A18)
      WRITE(*,106)MESS(3)
  106 FORMAT(6X,'LICHTENSTEIN',3X,'COOLING TOWERS',3X,A18)
      WRITE(*,107)
  107 FORMAT(6X,'DIRECT ENTRY',3X,'EITHER',13X,'NO RANGE
LIMITS')
      WRITE(*,100)
      WRITE(*,108)
  108 FORMAT(10X,'CHOOSE A NUMBER CORRESPONDING TO YOUR
CHOICE')
      WRITE(*,100)
      WRITE(*,109)
  109 FORMAT(7X,'1 -- USE SHULMAN, RECALCULATE FOR EACH
INCREMENT')
      WRITE(*,110)
  110 FORMAT(7X,'2 -- USE SHULMAN, CONSTANT AFTER INITIAL
EVALUATION')
```

```
      WRITE(*,111)
 111  FORMAT(7X,'3 -- USE NORMAN, CONSTANT AFTER INITIAL
EVALUATION')
      WRITE(*,112)
 112  FORMAT(7X,'4 -- USE LICHTENSTEIN, CONSTANT AFTER ',
     &'INITIAL EVALUATION')
      WRITE(*,113)
 113  FORMAT(7X,'5 -- ENTER kY`a DIRECTLY')
      WRITE(*,100)
      WRITE(*,114)
 114  FORMAT(7X,'TYPE THE NUMBER OF YOUR CHOICE NOW, THEN '
     &'PRESS RETURN')
      READ(*,*)M1C
      END
```

```
C
C     MENU2 SUBROUTINE -- SHOWS TRANSFER COEFFICIENTS
C
      SUBROUTINE MENU2(M2C,TG,TI,YPR,HTRAT,HGA,HLA,KPYA)
      IMPLICIT REAL*8 (A-Z)
      INTEGER M2C
      TF=(TI+TG)/2.0
      HGACC=KPYA*((SCG(TF)/PRG(TF))**(2./3.))*CPG(TF)
      HGAL=KPYA*CS(TG,YPR)
      HLACCS=HTRAT*HGACC
      HLALS=HTRAT*HGAL
      CALL SCREEN(21)
      WRITE(*,100)
 100  FORMAT(20X,'MASS AND HEAT TRANSFER COEFFICIENTS')
      WRITE(*,*)'     '
      WRITE(*,*)'     '
      WRITE(*,101)KPYA
 101  FORMAT(10X,'kY'a =  ',F8.4)
      WRITE(*,*)'     '
      WRITE(*,102)
 102  FORMAT(10X,'GAS PHASE HEAT TRANSFER COEFFICIENT
CHOICES:')
      WRITE(*,*)'     '
      WRITE(*,103)HGACC
 103  FORMAT(10X,'hga BY CHILTON COLBURN ANALOGY =  ',F7.1)
      WRITE(*,104)HGAL
 104  FORMAT(10X,'hga BY THE LEWIS ANALOGY =  ',F7.1)
      WRITE(*,*)'     '
      WRITE(*,105)
 105  FORMAT(10X,'LIQUID PHASE HEAT TRANSFER COEFFICIENTS')
      WRITE(*,106)
 106  FORMAT(10X,'** EXTRAPOLATED FROM PACKED BED DATA **')
      WRITE(*,*)'     '
      WRITE(*,107)HLACCS
 107  FORMAT(10X,'hla EXTRAPOLATED FROM CHILTON COLBURN =
',F10.1)
      WRITE(*,108)HLALS
 108  FORMAT(10X,'hla EXTRAPOLATED FROM LEWIS ANALOGY =
',F10.1)
      WRITE(*,*)'     '
      WRITE(*,109)
 109  FORMAT(10X,'MENU CHOICES -- CHOOSE A NUMBER, THEN
PRESS RETURN')
      WRITE(*,*)'     '
      WRITE(*,110)
 110  FORMAT(10X,' 1 -- ACCEPT kY'a, hga, hla FROM CHILTON
COLBURN')
      WRITE(*,111)
 111  FORMAT(10X,' 2 -- ACCEPT kY'a, hga, hla FROM LEWIS')
      WRITE(*,112)
 112  FORMAT(10X,' 3 -- ACCEPT kY'a, hga BY CHIL/COLB, ENTER
hla')
```

```
      WRITE(*,113)
 113  FORMAT(10X,' 4 -- ACCEPT kY`a, hga BY LEWIS, ENTER AN
hla')
      WRITE(*,114)
 114  FORMAT(10X,' 5 -- ENTER MY OWN kY`a, hga, hla')
      WRITE(*,115)
 115  FORMAT(10X,' 6 -- RETURN TO PREVIOUS MENU TO CHANGE
CHOICE')
      WRITE(*,*)'    '
      WRITE(*,116)
 116  FORMAT(10X,' VARIABLES IN CHOICES 1,3, AND 5 ARE
CONSTANTS')
      WRITE(*,117)
 117  FORMAT(10X,' kY`a IS UPDATED IN 2,4 BY THE LEWIS
ANALOGY')
      READ(*,*)M2C
      IF(M2C.EQ.6)RETURN
      IF(M2C.EQ.1)THEN
        HGA=HGACC
        HLA=HLACCS
        RETURN
      ELSEIF(M2C.EQ.2)THEN
        HGA=HGAL
        HLA=HLALS
        RETURN
      ELSEIF(M2C.EQ.3)THEN
        WRITE(*,*)'           ENTER hla TO BE USED'
        READ(*,*)HLA
        HGA=HGACC
        RETURN
      ELSEIF(M2C.EQ.4)THEN
        WRITE(*,*)'           ENTER hla TO BE USED'
        READ(*,*)HLA
        HGA=HGAL
        RETURN
      ELSE
        WRITE(*,*)'           ENTER kY`a, hga, hla VALUES TO
BE USED'
        READ(*,*)KPYA,HGA,HLA
        RETURN
      ENDIF
      END
```

```
C
C      THIS MENU IS PRESENTED UPON INTERRUPTION
C      TO CONTINUE OR TO CHANGE VARIABLES
C
      SUBROUTINE MENU3(M3C,DELZ,CRTHUM,NTERUP)
      IMPLICIT REAL*8 (A-Z)
      INTEGER M3C,NTERUP
      CALL SCREEN(40)
      WRITE(*,*)'          ACCESS MENU'
      WRITE(*,*)'      '
      WRITE(*,*)' CHOOSE A NUMBER, THEN PRESS RETURN'
      WRITE(*,*)'      '
      WRITE(*,*)'   0 - CONTINUE (NO CHANGES)'
      WRITE(*,*)'   1 - STOP HERE (GO TO PLOT SECTION)'
      WRITE(*,*)'   2 - DELTA Z'
      WRITE(*,*)'   3 - CRITICAL HUMIDITY'
      WRITE(*,*)'   4 - ACCESS FREQUENCY'
      WRITE(*,*)'   5 - RESTART (MULTIPLE CHANGES)'
      CALL SCREEN(5)
      READ(*,*)M3C
      IF(M3C.LT.2)RETURN
      IF(M3C.EQ.5)THEN
        CLOSE(10,STATUS='DELETE')
        WRITE(5,*)'      '
        RETURN
      ELSEIF(M3C.EQ.2)THEN
        WRITE(*,*)'      ENTER NEW DELTA-Z'
        READ(*,*)DELZ
      ELSEIF(M3C.EQ.3)THEN
        WRITE(*,*)'      ENTER NEW CRITICAL HUMIDITY'
        READ(*,*)CRTHUM
      ELSE
        CONTINUE
      ENDIF
      WRITE(*,*)'     ENTER NEW ACCESS FREQUENCY'
      READ(*,*)NTERUP
      END
```

```
C
C      MENU 4 PRESNTS THE END OF INTEGRATION CHOICES
C
       SUBROUTINE MENU4(ICH,M4C,LPR)
       INTEGER ICH,M4C
       REAL*8 LPR
       CALL SCREEN(21)
       WRITE(*,100)
 100   FORMAT(10X,'MENU CHOICES ARE:')
       WRITE(*,*)'       '
       WRITE(*,101)
 101   FORMAT(10X,' 0  -- CONTINUE WITH NEW L`1')
       WRITE(*,102)
 102   FORMAT(10X,' 1  -- GO TO PLOT NOW WITH THIS SET')
       WRITE(*,103)
 103   FORMAT(10X,' 2  -- CHANGE MASS OR HEAT TRANSFER
COEFFICIENTS')
       WRITE(*,104)
 104   FORMAT(10X,' 3  -- RETURN TO PRIMARY DATA INPUT AREA')

       CALL SCREEN(3)
       WRITE(*,105)
 105   FORMAT(10X,' ENTER YOUR CHOICE NOW:')
       READ(*,*)M4C
       END
```

PROCESS CALCULATIONS

```
C
C     THIS SUBROUTINE CALCULATES THE TRANSFER COEFFICIENTS
C
C
      SUBROUTINE TRXCOF(I,M1C,M2C,TI,TG,TL,
     &HGA,HLA,KPYA,LPR,GPR,YPR,CF,FD)
      IMPLICIT REAL*8 (A-Z)
      INTEGER I,M1C,M2C
      COMMON/BLOCK5/P7,P8,P9,P10,P11,P12,P13,
     &P14,P15,P16,P17,P18,P19,P20
      TF=(TG+TI)/2.0
      GPRS=GPR/(1.0+YPR)
      IF(M1C.LT.3)GO TO 20
      IF(M2C.EQ.0)THEN
        IF(M1C.EQ.3)THEN
          IF(LPR.GT.2.8544)THEN
            KPYA=1.562798829*(GPRS**0.8)
          ELSE
            KPYA=15.75402046*(0.01632299*LPR+0.0526)
     &      *(GPRS**0.8)
          ENDIF
          RETURN
        ELSEIF(M1C.EQ.4)THEN
          KPYA=0.333345564*(LPR**0.4)*(GPR**0.5)
          RETURN
        ELSE
          WRITE(*,*)'      ENTER kY'a DIRECTLY --',
     &'  UNITS ARE kg/m3-sec'
          READ(*,*)KPYA
          RETURN
        ENDIF
      ELSE
        IF((M2C.EQ.2).OR.(M2C.EQ.4))THEN
          KPYA=HGA/CS(TG,YPR)
        ENDIF
        RETURN
      ENDIF
 20   IF(M2C.EQ.7)RETURN
      IF(I.LT.5)THEN
        CALL CHAR(I,DS,M,N,P,EPSI,LPR,GPR,YPR,CF,FD)
        BETA=1.508*DS**(0.376)
        PHILSW=(2.47E-04)*DS**(-1.21)
        PHILTW=((2.09E-06)*(737.5*LPR)**BETA)/(DS**2)
        PHILOW=PHILTW-PHILSW
      ELSE
        CALL CHAR(I,DS,M,N,P,EPSI,LPR,GPR,YPR,CF,FD)
        BETA=1.508*DS**0.376
        PHILSW=(5.014E-05)*DS**(-1.56)
        PHILTW=((2.32E-06)*(737.5*LPR)**BETA)/(DS**2)
        PHILOW=PHILTW-PHILSW
      ENDIF
      AAW=M*(((808*GPR)/(RHOG(TF)**(0.5)))**N)*(LPR**P)
```

```
AVW=0.85*AAW*(PHILTW/PHILOW)
EPSILO=EPSI-PHILTW
G=GPR/28.97
JD=1.195*((DS*GPR)/(RMUG(TF)*(1.0-EPSILO)))**(-0.36)
KPRY=((JD*G)/(SCG(TF)**(2./3.)))*28.97
KPYA=KPRY*AVW
HG=(JD*CPG(TF)*GPR)/(PRG(TF)**(2./3.))
HGA=HG*AVW
A=(((DS*LPR)/RMUL(TL))**(0.45))*(PRL(TL)**(0.5))
HL=(25.1*RKTHL(TL)*A)/DS
HLA=HL*AVW
P7=BETA
P8=PHILSW
P9=PHILTW
P10=PHILOW
P11=AAW
P12=AVW
P13=EPSILO
P14=JD
P15=KPRY
P16=KPYA
P17=HG
P18=HGA
P19=HL
P20=HLA
END
```

```
C
C     THIS SUBROUTINE CALCULATES THE SHULMAN DATA
C
      SUBROUTINE SHUL(I,M1C,M2C,TI,TG,TL,HGA,HLA,KPYA,
     &LPR,GPR,YPR,TIC,ANS,IER)
      IMPLICIT REAL*8 (A-Z)
      INTEGER TIC,I,M1C,M2C,IER,J
      WRITE(*,*)'    ENTER PACKING NUMBER CHOICE'
      READ(*,*)I
        IF(TIC.EQ.1)THEN
          TI=TL
          DO 21 J=1,15
          CALL TRXCOF(I,M1C,M2C,TI,TG,TL,HGA,HLA,KPYA,
     &    LPR,GPR,YPR,CF,FD)
          SLOPE=0.-(HLA/(KPYA*1000.))
          CALL TITL(TL,TG,TI,YPR,SLOPE)
 21       CONTINUE
        ELSE
          TI=TL
          CALL TRXCOF(I,M1C,M2C,TI,TG,TL,HGA,HLA,KPYA,
     &    LPR,GPR,YPR,CF,FD)
        ENDIF
        WRITE(*,*)'  ENTER 0 TO PRINT TWO PAGES OF SHULMAN'
        WRITE(*,*)'  TRANSFER COEFFICIENT CALCULATIONS, OR'
        WRITE(*,*)'  ELSE ENTER 1 TO SKIP'
        CALL SCREEN(5)
        READ(*,*)ICH
        IF(ICH.EQ.0)CALL SHEG(TG,TL,TI,LPR,GPR)
      CALL CHAR(I,DS,M,N,P,EPSI,LPR,GPR,YPR,CF,FD)
      TY=(GPR**2)*CF*(RMUL(TL)**0.1)
      BY=RHOG(TG)*(1000.-RHOG(TG))
      YV=TY/BY
      XV=(LPR/GPR)*DSQRT(RHOG(TG)/(1000.-RHOG(TG)))
      CALL DELP(XV,YV,ANS,IER)
      IF(M1C.EQ.2)M2C=7
      END
```

```
C
C     THIS SUBROUTINE ASKS THE USER IF THEY WANT
C     TO SEE THE TWO PAGES OF SHULMAN CALCULATIONS
C
      SUBROUTINE SHEG(TG,TL,TI,LP,GP)
      IMPLICIT REAL*8 (A-Z)
      INTEGER SZE,I,P1
      CHARACTER NAME*13
      COMMON/BLOCK4/P1,P2,P3,P4,P5,P6
      COMMON/BLOCK5/P7,P8,P9,P10,P11,P12,P13,P14,P15,
     &P16,P17,P18,P19,P20
      I=P1
      DS=P2
      M=P3
      N=P4
      P=P5
      EPSI=P6
      BETA=P7
      PHILSW=P8
      PHILTW=P9
      PHILOW=P10
      AAW=P11
      AVW=P12
      EPSILO=P13
      JD=P14
      KPRY=P15
      KPYA=P16
      HG=P17
      HGA=P18
      HL=P19
      HLA=P20
      HGAL=950.*KPYA
      HGL=950.*KPRY
      IF(I.EQ.1)THEN
        SZE=13
        NAME='RASCHIG RINGS'
      ELSEIF(I.EQ.2)THEN
        SZE=25
        NAME='RASCHIG RINGS'
      ELSEIF(I.EQ.3)THEN
        SZE=38
        NAME='RASCHIG RINGS'
      ELSEIF(I.EQ.4)THEN
        SZE=50
        NAME='RASCHIG RINGS'
      ELSEIF(I.EQ.5)THEN
        SZE=13
        NAME='BERL SADDLES'
      ELSEIF(I.EQ.6)THEN
        SZE=25
        NAME='BERL SADDLES'
      ELSE
```

```
        SZE=38
        NAME='BERL SADDLES'
      ENDIF
      TF=(TG+TI)/2.
      NU=HL*DS/RKTHL(TL)
      CALL PAGEUP()
      WRITE(5,100)
 100  FORMAT(3X,'     ')
      WRITE(5,101)
 101  FORMAT(37X,'MASS AND HEAT TRANSFER COEFFICIENT',
     &' CALCULATIONS')
      WRITE(5,102)
 102  FORMAT(37X,47('='))
      WRITE(5,100)
      WRITE(5,103)
 103  FORMAT(13X,'Primary Reference :  Shulman et al, ',
     &'"Performance of Packed Columns", series of 5
articles,')
      WRITE(5,99)
  99  FORMAT(34X,'AIChE Journal, 1959 5(3) p. 290-294 (last
article)')
      WRITE(5,100)
      WRITE(5,100)
      WRITE(5,104)
 104  FORMAT(13X,'Adapted By:  Treybal, Robert E.  ',
     &'Mass Transfer Operations, 3rd Edition, 1980 p.
196-209')
      WRITE(5,100)
      WRITE(5,100)
      WRITE(5,105)
 105  FORMAT(15X,'SYMBOL',4X,'UNITS',15X,'DEFINITION')
      WRITE(5,106)
 106  FORMAT(15X,6('-'),4X,5('-'),15X,10('-'))
      WRITE(5,107)
 107  FORMAT(15X,'Phi',7X,'Dimensionless',7X,
     &'Holdup -- represents volume liquid/volume packed
column')
      WRITE(5,108)
 108  FORMAT(15X,'Ds',8X,'meters',14X,
     &'Diameter of an equivalent sphere')
      WRITE(5,109)
 109  FORMAT(15X,'Beta',6X,'Dimensionless',7x,'Exponent',
     &' Used in holdup calculations')
      WRITE(5,110)
 110  FORMAT(15X,'E',9X,'Dimensionless',7X,'Epsilon, ',
     &'dry bed voidage')
      WRITE(5,111)
 111  FORMAT(15X,'a',9X,'m2/m3',15X,'interfacial area')
      WRITE(5,112)
 112  FORMAT(15X,'jD',8X,'Dimensionless',7X,
     &'j factor for mass transfer')
      WRITE(5,113)
```

```
 113  FORMAT(15X,'jH',8X,'Dimensionless',7X,
     &'j factor for heat transfer')
      WRITE(5,114)
 114  FORMAT(15X,'kY`',8X,'kg/m2s-Delta Y`',5X
     &'mass transfer coefficient')
      WRITE(5,115)
 115  FORMAT(15X,'hg,hl',5X,'W/m2-K',14X,
     &'gas, liquid heat transfer coefficient')
      WRITE(5,116)
 116  FORMAT(15X,'Pr',8X,'Dimensionless',7x,'Prandtl
number')
      WRITE(5,117)
 117  FORMAT(15X,'Cp',8X,'N-m/kg-K',12X,'thermal heat
capacity')
      WRITE(5,118)
 118  FORMAT(15X,'Nu',8X,'Dimensionless',7X,'Nusselt
Number')
      WRITE(5,119)
 119  FORMAT(15X,'kthl',6X,'W/m-K',15X,'liquid thermal ',
     &'conductivity')
      WRITE(5,120)
 120  FORMAT(15X,'mu',8X,'kg/m-sec',12X,'viscosity')
      WRITE(5,121)
 121  FORMAT(15X,'Sc',8X,'Dimensionless',7X,'Schmidt
Number')
      WRITE(5,122)
 122  FORMAT(15X,'m,n,p',5x,'Dimensionless',7x,
     &'exponents used in interfacial area calculations')
      WRITE(5,123)
 123  FORMAT(15X,'Rhog',6X,'kg/m3',15X,'gas phase density')
      WRITE(5,100)
      WRITE(5,124)
 124  FORMAT(15X,'SUBSCRIPT',11X,'REFERS TO')
      WRITE(5,125)
 125  FORMAT(15X,9('-'),11X,9('-'))
      WRITE(5,126)
 126  FORMAT(15X,'Lo',18X,'operating or moving liquid')
      WRITE(5,127)
 127  FORMAT(15X,'Ls',18X,'static liquid')
      WRITE(5,128)
 128  FORMAT(15X,'Lt',18X,'total liquid')
      WRITE(5,129)
 129  FORMAT(15X,'W',19X,'water')
      WRITE(5,130)
 130  FORMAT(15X,'A',19X,'absorption')
      WRITE(5,131)
 131  FORMAT(15X,'V',19X,'vaporization')
      WRITE(5,132)
 132  FORMAT(15X,'l',19X,'liquid')
      WRITE(5,133)
 133  FORMAT(15X,'g',19X,'gas')
      WRITE(5,100)
```

```
      WRITE(5,134)
 134  FORMAT(42X,'VARIABLES AND OPERATIONAL PARAMETERS')
      WRITE(5,135)
 135  FORMAT(42X,36('='))
      WRITE(5,100)
      WRITE(5,100)
      WRITE(5,136)
 136  FORMAT(15X,2(10X,'VARIABLE',12X,'VALUE'))
      WRITE(5,137)
 137  FORMAT(15X,2(10X,25('-')))
      WRITE(5,138)NAME,PRG(TF)
 138  FORMAT(25X,'Packing Choice',6X,A13,2X,'Prg',18x,F5.2)
      WRITE(5,139)SZE,PRL(TL)
 139  FORMAT(25X,'Nominal Size
(mm)',3X,I3,12X,'Prl',18X,F5.2)
      WRITE(5,140)LP,SCG(TF)
 140  FORMAT(25X,'L Prime',13X,F5.2,10X,'Scg',19X,F4.2)
      WRITE(5,141)GP,CPG(TF)
 141  FORMAT(25X,'G Prime',13X,F5.2,10X,'Cpg',16X,F6.1)
      WRITE(5,142)+GP/28.97,RMUG(TF)
 142  FORMAT(25X,'G (G
Prime/28.97)',4X,F6.4,8X,'mug',19X,E12.6)
      WRITE(5,143)+TL-273.15,RMUL(TL)
 143  FORMAT(25X,'Liquid Temp',8X,F6.2,10X,'mul',19X,E12.6)
      WRITE(5,144)+TI-273.15,RKTHL(TL)
 144  FORMAT(25X,'Interface
Temp',5X,F6.2,10X,'kthl',18X,E12.6)
      WRITE(5,145)+TG-273.15,RHOG(TF)
 145  FORMAT(25X,'Gas Temp',11X,F6.2,10X,'Rhog',18X,F5.3)
      WRITE(5,146)+TF-273.15
 146  FORMAT(25X,'Film Temp',10X,F6.2)
      WRITE(5,100)
      WRITE(5,147)
 147  FORMAT(20X,'Note:  all gas phase variables are
evaluated ',
     &'at the film temperature -- T Film = (TG + TI)/2.0')
      WRITE(5,100)
      CALL PAGEUP()
      WRITE(5,100)
      WRITE(5,100)
      WRITE(5,150)
 150  FORMAT(18X,'HOLDUP CALCULATIONS',21X,'INTERFACIAL',
     &' AREA CALCULATIONS')
      WRITE(5,151)
 151  FORMAT(18X,6('='),1X,12('='),21X,11('='),1X,
     &4('='),1X,12('='))
      WRITE(5,100)
      WRITE(5,152)
 152  FORMAT(15X,'Treybal, Table 6.5, p. 206',
     &19X,'Treybal, Table 6.4, p. 205')
      WRITE(5,100)
      WRITE(5,100)
```

```
      WRITE(5,153)EPSI,LP
 153  FORMAT(15X,'Epsilon  =',4x,F5.3,28X,'L Prime = ',
     &F5.2,' Kg/m2-sec')
      WRITE(5,154)LP,M
 154  FORMAT(15X,'L Prime  =',3X,F5.2,2X,'kg/m2-sec',
     &20X,'m',5X,'= ',F5.2)
      WRITE(5,155)DS,N
 155  FORMAT(15X,'DS',7X,'=',4X,F6.4,' meters',22X,'n',
     &5X,'=  ',F6.4)
      WRITE(5,156)BETA,P
 156  FORMAT(15X,'Beta',5X,'=',4X,F6.4,29X,'p',5X,'= ',F6.3)
     WRITE(5,100)
      WRITE(5,157)PHILSW
 157  FORMAT(15X,'Phi-LsW  =',4X,F6.4,27X,
     &'aAW = (m*(808*G`/Rhog**0.5)**n)*L`**p')
      WRITE(5,158)PHILTW,AAW
 158  FORMAT(15X,'Phi-LtW  =',4X,F6.4,32X,'=  ',F5.2,'
m2/m3')
      WRITE(5,159)
 159  FORMAT(15X,'Phi-LoW  = (Phi-LtW) - (Phi-LsW)')
      WRITE(5,160)PHILOW
 160  FORMAT(24X,'=',4X,F7.5)
      WRITE(5,161)
 161  FORMAT(62X,'aVW = 0.85*aAW*(Phi-LtW/Phi-LoW)')
      WRITE(5,162)AVW
 162  FORMAT(67X,'=  ',F5.2,' m2/m3')
      WRITE(5,100)
      WRITE(5,100)
      WRITE(5,168)
 168  FORMAT(18X,'MASS TRANSFER EQUATIONS',22X,
     &'EQUATIONS EVALUATED')
      WRITE(5,169)
 169
FORMAT(18X,4('='),1X,8('='),1X,9('='),22X,9('='),1X,9('='))
    WRITE(5,100)
      WRITE(5,170)EPSI
 170  FORMAT(10X,'LIQUID PHASE (Used to determine hl)',15x,
     &'Epsilon  =  ',f5.3)
      WRITE(5,171)
 171  FORMAT(10X,6('-'),1X,5('-'))
      WRITE(5,172)
 172  FORMAT(60X,'ELo = E - (Phi-LtW)')
      WRITE(5,173)EPSILO
 173  FORMAT(17X,'(',5X,'(Ds*L`)',6X,')',28X,'=',6X,F5.3)
      WRITE(5,174)
 174  FORMAT(12X,'Nu = (25.1*(-----)**0.45)*(Prl**0.45)')
      WRITE(5,175)JD
 175  FORMAT(17X,'(',5X,'( mul )',6X,')',23X,'jd
=',3X,F8.5)
      WRITE(5,100)
      WRITE(5,176)KPRY
 176  FORMAT(10X,'GAS PHASE',41X,'kY  = ',3X,F8.5,
```

```
     &'  kg/m2-sec-Delta Y\'')
      WRITE(5,177)
 177  FORMAT(10X,3('-'),1X,5('-'))
      WRITE(5,178)NU
 178  FORMAT(23X,'(Ds*G Prime )',24X,'Nu  =   ',F8.2)
      WRITE(5,179)
 179  FORMAT(12X,'jd = 1.195*(-----------)**(-0.36)')
      WRITE(5,180)
 180  FORMAT(23X,'(mug*(1-ELo))',24X,'hg, Chilton Colburn')
      WRITE(5,181)HG
 181  FORMAT(64X,'=  ',F7.1,'  W/m2-K')
      WRITE(5,100)
      WRITE(5,183)
 183  FORMAT(17X,'jd =   kY*Scg**(2/3)',23X,'hg, Lewis')
      WRITE(5,184)HGL
 184  FORMAT(24X,13('-'),27X,'=  ',F7.1,'  W/m2-K')
      WRITE(5,185)
 185  FORMAT(29X,'G')
      WRITE(5,186)
 186  FORMAT(60X,'hl, from Nu = hl*Ds/kthl')
      WRITE(5,187)HL
 187  FORMAT(64X,'= ',F9.1,' W/m2-K')
      WRITE(5,188)
 188  FORMAT(18X,'HEAT TRANSFER EQUATIONS')
      WRITE(5,189)
 189  FORMAT(18X,4('='),1X,8('='),1X,9('='),18X,
     &'Corresponding Volumetric Coefficients')
      WRITE(5,190)
 190  FORMAT(59X,13('='),1X,10('='),1X,12('='))
      WRITE(5,191)
 191  FORMAT(10X,'CHILTON COLBURN ANALOGY:')
      WRITE(5,192)KPYA
 192  FORMAT(10X,7('-'),1X,7('-'),1X,8('-'),27X,
     &'kYaVW = ',F7.4,' kg/m3-sec-Delta Y\'')
      WRITE(5,193)HGA
 193  FORMAT(61X,'hgaVW (CC) =  ',F8.1,3X,'W/m3-K')
      WRITE(5,194)HLA
 194  FORMAT(28X,'hg',31X,'hlaVW',6X,'=  ',F9.1,'  W/m3-K')
      WRITE(5,195)HGAL
 195  FORMAT(16X,'jd = jh =  ----- *Prg**(2/3)',17X,
     &'hgaVW (Lewis) =  ',F8.1,'  W/m3-K')
      WRITE(5,201)
 201  FORMAT(27X,'Cp*G\'')
      WRITE(5,100)
      WRITE(5,196)
 196  FORMAT(10X,'LEWIS RELATION:')
      WRITE(5,197)
 197  FORMAT(10X,5('-'),1X,9('-'))
      WRITE(5,100)
      WRITE(5,198)
 198  FORMAT(20X,'hg')
      WRITE(5,199)
```

```
199   FORMAT(19X,'----  = 950 N-m/kg-K')
      WRITE(5,200)
200   FORMAT(20X,'kY')
      WRITE(5,100)
      END
```

```
C
C      SUBROUTINE FOR CALCULATING PRESSURE DROP
C      IN PACKED BEDS ONLY
C
C     SUBROUTINE DELP(X,Y,ANS,IER)
      IMPLICIT REAL*8 (A-Z)
      INTEGER I,IER,J,N1,M1,M2
      REAL*8 L(6),PD(6),XX(20),AB(6,20),BC(6,20),
     &CC(6,20),DE(6,20)
      OPEN(12,FILE='PDROP.DAT',STATUS='OLD')
      REWIND(12)
      DO 4 M1=1,100
      DO 4 M2=1,6
      READ(12,101,END=6)XX(M1),AB(M2,M1),BC(M2,M1),
     &CC(M2,M1),DE(M2,M1)
    4 CONTINUE
    6 N1=M1-1
  101 FORMAT(1X,F7.2,1X,3(E16.9,1X),F11.6)
      IER=0
      IF(X.LT.0.015)X=0.0151
      IF(X.GT.2.0)THEN
        IER=1
        RETURN
      ENDIF
      PD(1)=50.
      PD(2)=100.
      PD(3)=200.
      PD(4)=400.
      PD(5)=800.
      PD(6)=1200.
      DO 10 I=1,N1
      IF((X.GE.XX(I)).AND.(X.LT.XX(I+1)))THEN
        GO TO 12
      ENDIF
   10 CONTINUE
   12 S=X-XX(I)
      DO 15 J=1,6
      L(J)=((AB(J,I)*S+BC(J,I))*S+CC(J,I))*S+DE(J,I)
   15 CONTINUE
      IF(Y.LT.L(1))THEN
        IER=2
        RETURN
      ELSEIF(Y.GE.L(6))THEN
        IER=3
        RETURN
      ELSE
        DO 20 I=1,5
          IF((Y.GE.L(I)).AND.(Y.LT.L(I+1)))THEN
            ANS=PD(I)+((Y-L(I))/(L(I+1)-L(I)))*
     &(PD(I+1)-PD(I))
            RETURN
          ENDIF
```

```
20    CONTINUE
    ENDIF
```

```
C
C      THE SHULMAN CALCULATIONS NEED CHARACTERISTIC
C      PACKING INFORMATION -- THIS ROUTINE PASSES
C      THE NECESSARY INFORMATION
C
       SUBROUTINE CHAR(I,DS,M,N,P,EPSI,LPR,GPR,YPR,CF,FD)
       IMPLICIT REAL*8 (A-Z)
       INTEGER I,P1
       COMMON/BLOCK4/P1,P2,P3,P4,P5,P6
       IF(I.EQ.1)THEN
         DS=0.0177
         EPSI=0.63
         CF=580
         FD=2860
         IF(LPR.LT.2.0)THEN
           M=28.01
           N=0.2323*LPR-0.3
           P=-1.04
         ELSE
           M=14.69
           N=0.01114*LPR+0.148
           P=-0.111
         ENDIF
       ELSEIF(I.EQ.2)THEN
         DS=0.0356
         EPSI=0.73
         CF=155
         FD=3270
         IF(LPR.LT.2.0)THEN
           M=34.42
           N=0
           P=0.552
         ELSE
           M=68.2
           N=0.0389*LPR-0.0793
           P=-0.47
         ENDIF
       ELSEIF(I.EQ.3)THEN
         DS=0.0530
         EPSI=0.71
         CF=95
         FD=2042
         IF(LPR.LT.2.0)THEN
           M=36.5
           N=0.0498*LPR-0.1013
           P=0.274
         ELSE
           M=40.11
         N=0.01091*LPR-0.022
         P=0.14
       ENDIF
       ELSEIF(I.EQ.4)THEN
```

```
  DS=0.0725
  EPSI=0.74
  CF=65
  FD=2042
  IF(LPR.LT.2.0)THEN
    M=31.52
    N=0
    P=0.481
  ELSE
    M=34.03
    N=0
    P=0.362
  ENDIF
  ELSEIF(I.EQ.5)THEN
  DS=0.31622
  EPSI=0.63
  CF=240
  FD=2042
  IF(LPR.LT.2.0)THEN
    M=16.28
    N=0.0529
    P=0.761
  ELSE
    M=25.61
    N=0.0529
    P=0.170
  ENDIF
ELSEIF(I.EQ.6)THEN
DS=0.0320
EPSI=0.69
  CF=110
  FD=2041
IF(LPR.LT.2.0)THEN
  M=52.14
  N=0.0506*LPR-0.1029
  P=0
ELSE
  M=73.
  N=0.0310*LPR-0.0630

  P=-0.359
ENDIF
ELSE
  DS=0.0472
  EPSI=0.75
  CF=65
  FD=2042
  IF(LPR.LT.2.0)THEN
    M=40.6
    N=-0.0508
    P=0.455
  ELSE
```

```
    M=62.4
    N=0.0240*LPR-0.0996
    P=-0.1355
  ENDIF
ENDIF
P1=I
P2=DS
P3=M
P4=N
P5=P
P6=EPSI
END
```

```
C
C      THIS SUBROUTINE CALCULATES THE RELATIVE HUMIDITY
C
       SUBROUTINE RELHUM(TG,YPR,RH)
       IMPLICIT REAL*8 (A-Z)
       CALL YSATPR(TG,YPS,PSAT)
       YNO=(28.97/18.02)*YPR
       RH=100.*(YNO/(1.+YNO))*14.696/PSAT
       END
```

```
C
C     THIS SUBROUTINE CHECKS FOR SATURATION
C     OF THE GAS STREAM
C
      SUBROUTINE SATF(SFC,GPR1)
      IMPLICIT REAL*8 (A-Z)
      INTEGER SFC
        WRITE(5,881)
 881    FORMAT(8X,'RUN TERMINATED- SATURATION ACHIEVED')
        WRITE(5,*)'       '
      WRITE(*,*)'  SATURATION ACHIEVED -- RUN TERMINATED'
      WRITE(*,*)'       '
      WRITE(*,*)'  TYPE THE NUMBER OF YOUR CHOICE, THEN
RETURN'
      WRITE(*,*)'       '
      WRITE(*,*)'  1 -- INCREASE G PRIME, OTHER INPUTS
CONSTANT'
      WRITE(*,*)'  2 -- RETURN TO INITIAL DATA ENTRY POINT'
      WRITE(*,*)'  3 -- GO TO PLOT ROUTINE WITH THIS SET'
      WRITE(*,*)'  4 -- CHANGE HEAT OR MASS TRANSFER
COEFFICIENTS'
      WRITE(*,*)'       '
      CALL SCREEN(5)
      READ(*,*)SFC
      IF (SFC.EQ.1)THEN
        WRITE(*,*)'   PREVIOUS G PRIME WAS --   ',GPR1
        WRITE(*,*)'   ENTER NEW G PRIME '
        READ(*,*)GPR1
        WRITE(5,*)'       '
      ENDIF
      END
```

```
C
C       SUBROUTINE FOR CALCULATING THE INTERFACE TEMPERATURE
C
      SUBROUTINE TITL(TL,TG,TI,YPR,SLOPE)
      IMPLICIT REAL*8 (A-Z)
      INTEGER I,J,NN
      TID=TL-273.15
   10 CALL YSATPR(TID+273.15,YPS,PSAT)
      HPRI=HPRIME(TID,YPS)/1000.
      DUM=HPRIME(TG-273.15,YPR)/1000.
      TI=((HPRI-DUM)/SLOPE)+(TL-273.15)
      IF(DABS(TID-TI).GT.0.0005)THEN
        TID=TI
        GO TO 10
      ENDIF
      TI=TI+273.15
      END
```

```
C
C       THIS IS THE OVERALL BALANCE, USED TO
C       CALCULATE EITHER A NEW L PRIME AT THE
C       BOTTOM OF THE COLUMN, OR ELSE A NEW
C       VALUE OF LIQUID TEMP IS THE INTERFACE
C       EQUATION PREDICTS A TEMP TOO CLOSE TO TL.
C
      SUBROUTINE OVRALL(L2,L1,GS,Y2,Y1,TG2,TG1,TL1,TL2,IC)
      IMPLICIT  REAL*8 (A-Z)
      INTEGER IC
      L0=2502300.
      T0=273.15
      A=L0*(Y2-Y1)
      B=0.-CS(TG1,Y1)*(TG1-T0)
      C=CS(TG2,Y2)*(TG2-T0)
      A=GS*(A+B+C)
      IF(IC.EQ.0)THEN
        B=(L2-L1)*4178.*T0
        C=L1*4178*TL1
        TL2=(A+B+C)/(L2*4178.)
      ELSE
        B=L2*4178.*(TL2-T0)
        L1=(B-A)/(4178.*(TL1-T0))
      ENDIF
      RETURN
      END
```

PROGRAM UTILITIES AND I/O CONTROL

```
C
C     THIS SUBROUTINE GETS ALL THE INITIAL DATA
C     FROM THE USER FOR PROGRAM INPUTS
C
      SUBROUTINE INPUTS(TL2,TL1,TG1,LPR2,GPR1,YPR1,
     &LFACT,DELZ,CRTHUM,NTERUP,TIC)
      IMPLICIT REAL*8 (A-Z)
      INTEGER NTERUP,TIC
      CALL SCREEN(21)
      WRITE(*,601)
 601  FORMAT(10X,'PRIMARY DATA INPUT AREA')
      WRITE(*,*)'    '
      WRITE(*,602)
 602  FORMAT(10X,'PLEASE ENTER EACH VALUE WHEN REQUESTED')
      WRITE(*,603)
 603  FORMAT(10X,'REMEMBER TO PRESS RETURN AFTER EACH ENTRY
!!!')
      WRITE(*,*)'     '
      WRITE(*,604)
 604  FORMAT(10X,'ENTER ALL TEMPERATURES IN DEGREES C')
      WRITE(*,*)
      WRITE(*,605)
 605  FORMAT(10X,'INLET WATER TEMPERATURE, TL2:')
      READ(*,*)TL2
      WRITE(*,606)
 606  FORMAT(10X,'OUTLET WATER TEMPERATURE, TL1:')
      READ(*,*)TL1
      WRITE(*,607)
 607  FORMAT(10X,'ENTERING GAS TEMPERATURE, TG1:')
      READ(*,*)TG1
      WRITE(*,608)
 608  FORMAT(10X,'FLOWRATE UNITS SHOULD BE: kg/m2-sec')
      WRITE(*,*)'      '
      WRITE(*,609)
 609  FORMAT(10X,'LIQUID FLOW RATE INTO THE UNIT:')
      READ(*,*)LPR2
      WRITE(*,610)
 610  FORMAT(10X,'GAS FLOW RATE INTO THE UNIT')
      READ(*,*)GPR1
      WRITE(*,611)
 611  FORMAT(10X,'Y`, ABSOLUTE HUMIDITY OF ENTERING GAS')
      READ(*,*)YPR1
      WRITE(*,612)
 612  FORMAT(10X,'FIRST GUESS FOR EVAPORATION LOSS:')
      WRITE(*,*)'      '
      WRITE(*,613)
 613  FORMAT(10X,' 0 -- ENTER L`1 DIRECTLY')
      WRITE(*,614)
 614  FORMAT(10X,' 1 -- ENTER EVAPORATION LOSS (DECIMAL
FORM)')
      WRITE(*,629)
 629  FORMAT(10X,' 2 -- USE 0.1% EVAP. PER DEG. F OF RANGE')
```

```
      WRITE(*,*)'      '
      WRITE(*,615)
 615  FORMAT(10X,' ENTER 0, 1, OR 2 NOW:')
      READ(*,*)ICH
      IF(ICH.EQ.0)THEN
        WRITE(*,616)
 616    FORMAT(10X,' ENTER L`1 -- Kg/m2-sec')
        READ(*,*)LPR1
        LFACT=1.0-(LPR1/LPR2)
      ELSEIF(ICH.EQ.1)THEN
        WRITE(*,617)
 617    FORMAT(10X,'ENTER EVAPORATION LOSS IN DECIMAL FORM')

        WRITE(*,618)
 618    FORMAT(10X,'FOR EXAMPLE, 5% IS ENTERED AS 0.05')
        READ(*,*)LFACT
      ELSE
        LFACT=0.001*(1.8*(DABS(TL2-TL1)))
      ENDIF
      WRITE(*,619)
 619  FORMAT(10X,'ENTER INCREMENT HEIGHT, DELTA - Z, IN
METERS')
      READ(*,*)DELZ
      WRITE(*,620)
 620  FORMAT(10X,'ENTER CRITICAL RELATIVE HUMIDITY')
      READ(*,*)CRTHUM
      WRITE(*,621)
 621  FORMAT(10X,'ENTER ACCESS FREQUENCY')
      READ(*,*)NTERUP
      WRITE(*,*)'      '
      WRITE(*,622)
 622  FORMAT(10X,'YOU HAVE A CHOICE OF HOW TI, THE
INTERFACE')
      WRITE(*,623)
 623  FORMAT(10X,'TEMPERATURE, IS CALCULATED -- REMEMBER
THAT')
      WRITE(*,624)
 624  FORMAT(10X,'CALCULATING TI MAY YIELD LARGE ERRORS IF')

      WRITE(*,625)
 625  FORMAT(10X,'hla/kY`a IS NOT LARGE')
      WRITE(*,*)'      '
      WRITE(*,626)
 626  FORMAT(10X,' 0 -- USE TI=TL THROUGHOUT')
      WRITE(*,627)
 627  FORMAT(10X,' 1 -- CALCULATE TI AT EACH POINT')
      WRITE(*,628)
 628  FORMAT(10X,' CHOOSE 0 OR 1 NOW:')
      READ(*,*)TIC
      TL2=TL2+273.15
      TL1=TL1+273.15
```

```
TG1=TG1+273.15
END
```

```
C
C  THIS PRINTS THE DATA HEADER
C
      SUBROUTINE HEADER()
      WRITE(5,100)
 100  FORMAT(10X,'GAS STREAM',19X,'PROCESS ENERGY',14X,
     &'TEMPERATURES IN',23X,'HEAT AND MASS')
      WRITE(5,101)
 101  FORMAT(9X,'MASS TRANSFER',18X,'AND MASS DATA',13X,
     &'DEGREES CENTIGRADE',17X,'TRANSFER COEFFICIENTS')
      WRITE(5,102)
 102  FORMAT(1X,30('='),2X,28('='),2X,24('='),10X,30('='))
      WRITE(5,*)'       '
      WRITE(5,103)
 103  FORMAT(1X,'SATURATION',2X,'BULK GAS',2X,'RELATIVE',
     &2X,'BULK GAS',3X,'LIQUID',5X,'GAS',24X,'BULK',13X,
     &'GAS',6X,'LIQUID',6X,'MASS')
      WRITE(5,104)
 104  FORMAT(1X,'HUMIDITY',4X,'HUMIDITY',2X,'HUMIDITY',
     &2X,'ENTHALPY',4X,'RATE',6X,'RATE',4X,'LIQUID',2X,
     &'INTERFACE',2X,'GAS',4X,'HEIGHT',4X,'hga',8X,
     &'hla',8X,'kY'a')
      WRITE(5,105)
 105  FORMAT(2X,'(kg/kg)',5X,'(kg/kg)',4x,'(%)',5X,
     &'(kJ/kg)',3x,'(kg/m2s)',2X,'(kg/m2s)',3X,'(C)',
     &7X,'(C)',5x,'(C)',6x,'(m)',3x,'(W/m3sK)',3x,
     &'(W/m3sK)',3x,'(Kg/m3s)')
      WRITE(5,106)
 106  FORMAT(1X,10('-'),5(2X,8('-')),2X,6('-'),2X,
     &9('-'),2X,5('-'),2X,6('-'),2X,8('-'),2X,
     &10('-'),2X,8('-'))
      END
```

```
C
C     THIS SUBROUTINE WRITES THE INTEGRATION NUMBER
C
      SUBROUTINE HEADL(INT)
      INTEGER INT
      WRITE(5,100)
 100  FORMAT(5X,'     ')
      WRITE(5,101)
 101  FORMAT(49X,'PACKED COLUMN/COOLING TOWER DESIGN')
      WRITE(5,100)
      WRITE(5,102)+INT+1
 102  FORMAT(55X,'INTEGRATION NUMBER ',I2)
      WRITE(5,100)
      WRITE(5,100)
      END
```

```
C
C      THIS SUBROUTINE PRINTS ALL THE INITIAL
C      RUN INFORMATION.
C
      SUBROUTINE DIAG(TL2,TL1,L2,DELZ,TG1,Y1,G1,GS1,CH,
     &M1C,PD,FP,IER)
      IMPLICIT REAL*8 (A-Z)
      CHARACTER MESS*27
      INTEGER IER
      INTEGER M1C,J,INT
      WRITE(5,98)
 98   FORMAT(2X,'       ')
      WRITE(5,98)
      WRITE(5,100)TL2
 100  FORMAT(20X,'TL2 =  ',F5.2,20X,'TG2  unknown',
     &11X,'VARIABLE      UNITS')
      WRITE(5,101)L2
 101  FORMAT(20X,'L`2 =   ',F5.3,3X,
     &'====>X  X====>  ','Y`2  unknown',11X,23('-'))
      WRITE(5,102)
 102  FORMAT(41X,'X  X',30X,'TEMPERATURES  DEGREES C')
      WRITE(5,103)
 103  FORMAT(41X,'X  X',30X,'FLOW RATES    kg/m2-sec')
      WRITE(5,104)
 104  FORMAT(38X,10('X'))
      WRITE(5,105)
 105  FORMAT(27X,'Z PLUS     X   2.   X')
      WRITE(5,106)
 106  FORMAT(26X,'DELTA Z ----X--------X----')
      WRITE(5,107)DELZ
 107  FORMAT(38X,'X',8X,'X',5X,'DELTA Z = ',F5.3,' meters')
      WRITE(5,108)
 108  FORMAT(32X,'Z ----X--------X----')
      WRITE(5,109)
 109  FORMAT(38X,'X',8X,'X',27X,'DESIGN PARAMETERS')
      WRITE(5,110)
 110  FORMAT(38X,'X   1.   X',27X,43('-'))
      WRITE(5,111)
 111  FORMAT(38X,10('X'))
      WRITE(5,112)CH
 112  FORMAT(41X,'X  X',30X,'CRITICAL RELATIVE ',
     &'HUMIDITY  =  ',F5.1)
      WRITE(5,113)TL1,TG1,+L2/G1
 113  FORMAT(20X,'TL1 =  ',F5.2,9X,'X  X',7X,
     &'TG1  =  ',F5.2,10X,'L/G RATIO =  ',F4.2)
      WRITE(5,114)Y1
 114  FORMAT(20X,'L`1  unknown  <====X  X<====  ',
     &'Y`1  =   ',F6.4)
      IF(IER.EQ.1)THEN
        MESS=' ** X VALUE OUT OF RANGE **'
      ELSEIF(IER.EQ.2)THEN
        MESS=' ** LESS THAN 50 (N/m2) **'
```

```
      ELSE
        MESS=' **  AT FLOOD POINT **'
      ENDIF
      IF(M1C.LT.3)THEN
      IF(IER.EQ.0)THEN
        WRITE(5,115)G1,PD
      ELSE
        WRITE(5,116)G1,MESS
      ENDIF
      ELSE
        WRITE(5,117)G1
      ENDIF
      IF(M1C.LT.3)THEN
      WRITE(5,118)GS1,FP
      ELSE
        WRITE(5,119)GS1
      ENDIF
      WRITE(5,98)
      WRITE(5,98)
      WRITE(5,98)
115   FORMAT(52X,'G`1  =   ',F5.3,10X,'PRESSURE DROP  = ',
     &F6.1,' (N/m2) per m packing')
116   FORMAT(52X,'G`1  =   ',F5.3,10X,A28)
117   FORMAT(52X,'G`1  =   ',F5.3)
118   FORMAT(52X,'G`S  =   ',F5.3,10X,'FLOOD POINT    = ',
     &F6.1,'(N/m2) per m of packing')
119   FORMAT(52X,'G`S  =   ',F5.3)
      END
```

```
C
C     THIS SUBROUTINE DOES AN OVERALL BALANCE
C     TO CALCULATE THE MASS AND ENERGY LOSSES
C
      SUBROUTINE ENDINT(L1,L2,L2A,Y1,Y2,GS,TG1,TG2,TL1,
     &TL2,I,TIC)
      IMPLICIT REAL*8 (A-Z)
      INTEGER I,TIC,J
      LHSM=L2-L1
      RHSM=GS*(Y2-Y1)
      A=L2*4178*(TL2-273.15)
      B=L1*4178.*(TL1-273.15)
      LHSE=(A-B)/1000.
      A=HPRIME(TG2-273.15,Y2)
      B=HPRIME(TG1-273.15,Y1)
      RHSE=GS*(A-B)/1000.
      PDIF=(DABS(RHSE-LHSE)/LHSE)*100.
      WRITE(5,100)
 100  FORMAT(3X,'      ')
      WRITE(5,100)
      WRITE(5,101)+I+1
 101  FORMAT(10X,'INTEGRATION NUMBER ',I2,' COMPLETE')
      WRITE(5,100)
      WRITE(5,102)
 102  FORMAT(17X,'MASS BALANCE:  L`2 - L`1 = G`s*'
     &'(Y`2 - Y`1)')
      WRITE(5,103)
 103  FORMAT(17X,4('-'),1X,7('-'))
      WRITE(5,100)
      WRITE(5,104)LHSM
 104  FORMAT(30X,'LIQUID LOSS = ',F8.5,' kg/m2-sec')
      WRITE(5,100)
      WRITE(5,105)RHSM
 105  FORMAT(30X,'VAPOR GAIN  = ',F8.5,' kg/m2-sec')
      WRITE(5,100)
      WRITE(5,106)
 106  FORMAT(17X,'ENERGY BALANCE:',
     &'  L`2*Hal2 - L`1*Hal1 = G`s*(H`2 - H`1)')
      WRITE(5,107)
 107  FORMAT(17X,6('-'),1X,7('-'))
      WRITE(5,100)
      WRITE(5,108)LHSE
 108  FORMAT(20X,'ENERGY LOST BY LIQUID =',4X,
     &F9.4,' kJ/m2-sec')
      WRITE(5,100)
      WRITE(5,109)RHSE
 109  FORMAT(20X,'ENERGY GAINED BY GAS  =',4X,
     &F9.4,' kJ/m2-sec')
      WRITE(5,100)
      WRITE(5,110)PDIF
 110  FORMAT(20X,'PERCENT DIFFERENCE BASED ON LIQUID  =',
     &'  ',F4.1,' %')
```

```
      WRITE(5,100)
      DL=L2-L2A
      L1N=L1-DL
      DIF=DABS(L1N-L1)
      WRITE(5,116)L1N,DIF
116   FORMAT(20X,'NEW L PRIME 1 =',F10.7,10X,'DIF =',F12.8)
      OPEN(11,FILE='NTG.DAT',STATUS='OLD')
      ACC=0.
      REWIND(11)
      READ(11,*)XO,YO
      DO 117 J=1,1000
        READ(11,*,END=118)XN,YN
        YAV=(YN+YO)/2.0
        DELX=XN-XO
        ACC=ACC+YAV*DELX
        XO=XN
        YO=YN
117   CONTINUE
118   WRITE(5,100)
      WRITE(5,119)ACC
119   FORMAT(20X,'NTU = ',F7.4)
      WRITE(5,100)
      CLOSE(11,STATUS='DELETE')
      END
```

```
C
C       THIS SUBROUTINE SCROLLS THE SCREEN
C       UPWARD BY THE NUMBER SENT TO IT.
C
      SUBROUTINE SCREEN(N)
      DO 10 I=1,N
      WRITE(*,*)'       '
   10 CONTINUE
      END
```

```
C
C      THIS SCREEN ASKS THE USER TO MOVE THE PAPER UP
C
      SUBROUTINE PAGEUP()
      CALL SCREEN(20)
      WRITE(*,*)'  SET PRINTER TO THE TOP OF A NEW PAGE ---'

      WRITE(*,*)'      '
      WRITE(*,*)'  PRESS ZERO (0), THEN RETURN WHEN READY'
      CALL SCREEN(15)
      READ(*,*)A
      END
```

```
C
C      THIS IS THE PLOTTING SUBROUTINE
C
      SUBROUTINE PLOT()
      IMPLICIT REAL*8 (A-H,O-Z)
      IMPLICIT INTEGER (I-N)
      REAL*8 TG(500),TL(500),TP(13)
      REAL*8 HPR(500),LIQ,HPRS(500),TS(500)
      CHARACTER LINE(121)*1,MESS*100
      OPEN(11,FILE='PROG.DAT',STATUS='OLD')
      OPEN(12,FILE='SAT.DAT',STATUS='OLD')
      REWIND 12
      REWIND 11
      DO 10 I=1,500
      READ(11,*,END=11)TG(I),TL(I),HPR(I)
   10 CONTINUE
   11 I=I-1
      ICNT=I
      DO 20 NN=1,500
   20 READ(12,*,END=21)TS(NN),HPRS(NN)
   21 NN=NN-1
      IF(TG(1).LT.TL(1))THEN
        STMAX=TG(1)
        STMIN=TL(ICNT)
      ELSE
        STMAX=TL(1)
        STMIN=TL(ICNT)
      ENDIF
      HMAX=HPR(1)
      HMIN=HPR(ICNT)
      CALL YSATPR(STMAX+273.15,YPSTAR,PSAT)
      CALL YSATPR(STMIN+273.15,YPSTOP,PSAT)
      STARSH=HPRIME(STMAX,YPSTAR)/1000.
      STOPSH=HPRIME(STMIN,YPSTOP)/1000.
   14 CALL SCREEN(21)
      WRITE(*,200)
  200 FORMAT(20X,'PLOTTING SUBROUTINE')
      WRITE(*,201)
  201 FORMAT(5X,'       ')
      WRITE(*,202)
  202 FORMAT(6X,'ENTHALPY AND TEMPERATURE RANGES ARE',
     &' NEEDED TO SCALE THE PLOT')
      WRITE(*,201)
      WRITE(*,203)
  203 FORMAT(6X,'FOLLOW THE GUIDELINES BELOW TO SEE ALL ',
     &'OF THE DESIGN PROFILES')
      WRITE(*,204)
  204 FORMAT(14X,'** OTHERWISE SOME OF THE DATA WILL ',
     &'NOT BE PLOTTED **')
      WRITE(*,205)
  205 FORMAT(6X,'TO INCLUDE THE SATURATION ENTHALPY LINE,'
     &' SET THE STOP ENTHALPY ABOVE')
```

```
      WRITE(*,206)
 206  FORMAT(6X,'THE VALUE GIVEN AT THE STARTING
TEMPERATURE')
      WRITE(*,201)
      WRITE(*,207)STMAX
 207  FORMAT(6X,'START TEMPERATURE SHOULD BE BELOW',4X,
     &F4.1,' DEG. C')
      WRITE(*,208)STMIN
 208  FORMAT(6X,'STOP TEMPERATURE SHOULD BE ABOVE',4X,
     &F4.1,' DEG. C')
      WRITE(*,201)
      WRITE(*,209)HMAX
 209  FORMAT(6X,'START ENTHALPY SHOULD BE BELOW',4X,
     &F6.1,' kJ/kg')
      WRITE(*,210)HMIN
 210  FORMAT(6X,'STOP ENTHALPY SHOULD BE ABOVE',4X,
     &F6.1,' kJ/kg')
      WRITE(*,201)
      WRITE(*,211)STMAX,STARSH
 211  FORMAT(6X,'FOR A START TEMP. OF ',F5.1,
     &', SATURATION ENTHALPY IS ',F6.1,' kJ/kg')
      WRITE(*,212)STMIN,STOPSH
 212  FORMAT(6X,'FOR A STOP TEMP. OF ',F5.1,
     &', SATURATION ENTHALPY IS ',F6.1,' kJ/kg')
      WRITE(*,*)'       '
      WRITE(*,*)'       '
      WRITE(*,*)'       '
      WRITE(*,*)'  ENTER START AND STOP TEMPERATURES - DEG.
C'
      WRITE(*,*)'     SEPARATE THEM BY A COMMA, THEN PRESS
RETURN'
      READ(*,*)TSTART,TSTOP
      WRITE(*,*)'  ENTER START AND STOP ENTHALPIES - kJ/kg'
      WRITE(*,*)'     SEPARATE THESE VALUES BY A COMMA,
ALSO'
      READ(*,*)HSTART,HSTOP
      TP(1)=TSTART
      TP(13)=TSTOP
      TINC=(TSTOP-TSTART)/12.
      WRITE(*,107)
 107  FORMAT(6X,'ENTER PLOT TITLE IN APOSTROPHE MARKS')
      READ(*,*)MESS
      CALL PAGEUP()
      WRITE(5,*)'       '
      WRITE(5,108)MESS
 108  FORMAT(20X,A101)
      WRITE(5,*)'      '
      DO 17 JJJ=1,11
      TP(JJJ+1)=TSTART+JJJ*TINC
  17  CONTINUE
      WRITE(5,26)(TP(L),L=1,13)
  26  FORMAT(12X,F4.1,4X,11(F4.1,6X),F4.1)
```

```
      WRITE(5,27)
 27   FORMAT(12X,12('+---------'),'+')
      HINC=(HSTOP-HSTART)/43.
      DO 375 K=0,43
        HVAL=HSTOP-K*HINC
        DO 25 L=1,120
 25       LINE(L)=' '
        IF((HVAL.LT.HPR(ICNT)).AND.(HVAL.GE.HPR(1)))THEN
          DO 30 L=1,ICNT
            IF((HVAL.GT.HPR(L)).AND.(HVAL.LE.HPR(L+1)))THEN
              GO TO 31
            ENDIF
 30       CONTINUE
 31       GAS=TG(L)+((HVAL-HPR(L))/(HPR(L+1)-HPR(L)))*
     &          (TG(L+1)-TG(L))
          LIQ=TL(L)+((HVAL-HPR(L))/(HPR(L+1)-HPR(L)))*
     &          (TL(L+1)-TL(L))
          GAS=(GAS-TSTART)/(TSTOP-TSTART)
          LIQ=(LIQ-TSTART)/(TSTOP-TSTART)
        ELSE
          GAS=0
          LIQ=0
        ENDIF
        DO 35 L=1,NN
          IF((HVAL.GT.HPRS(L)).AND.(HVAL.LE.HPRS(L+1)))THEN
            GO TO 36
          ENDIF
 35     CONTINUE
 36     SAT=TS(L)+((HVAL-HPRS(L))/(HPRS(L+1)-HPRS(L)))*
     &        (TS(L+1)-TS(L))
        IF((SAT.LT.TSTART).OR.(SAT.GT.TSTOP))THEN
          SAT=0
        ENDIF
        SAT=(SAT-TSTART)/(TSTOP-TSTART)
        ISAT=DINT(121.*SAT+0.5)
        IGAS=DINT(121.*GAS+0.5)
        ILIQ=DINT(121.*LIQ+0.5)
        LINE(ISAT+1)='*'
        LINE(IGAS+1)='G'
        LINE(ILIQ+1)='L'
        LINE(1)='¦'
        LINE(121)='¦'
        WRITE(5,50)HVAL,(LINE(LL),LL=1,121)
 50     FORMAT(1X,F6.2,5X,121A1)
375   CONTINUE
      WRITE(5,27)
      WRITE(5,26)(TP(L),L=1,13)
      WRITE(5,*)'       '
      WRITE(5,*)'       '
      WRITE(5,69)
      WRITE(5,*)'       '
 69   FORMAT(50X,'X AXIS:  TEMPERATURE, DEGREES CENTIGRADE')
```

```
      WRITE(5,70)
70    FORMAT(54X,'Y AXIS:  ENTHALPY, kJ/kg DRY AIR')
      WRITE(5,*)'      '
      CALL SCREEN(21)
      WRITE(*,*)'       ENTER 1, THEN RETURN, TO PLOT AGAIN'
      WRITE(*,*)'       PRESS ANY OTHER NUMBER TO CONTINUE'
      CALL SCREEN(10)
      READ(*,*)IS
      IF(IS.EQ.1)GO TO 14
      RETURN
      END
```

FUNCTIONS AND OTHER SUBROUTINES

```
C
C     SCHMIDT NUMBER, GAS
C
      REAL*8 FUNCTION SCG(TF)
      IMPLICIT REAL*8 (A-Z)
      SCG=RMUG(TF)/(RHOG(TF)*DAB(TF))
      RETURN
      END
```

```
C
C     GAS PHASE DIFFUSIVITY
C
      REAL*8 FUNCTION DAB(TF)
      IMPLICIT REAL*8 (A-Z)
      DAB=(2.634/101325)*(TF/298.15)**(1.5)
      RETURN
      END
```

```
C
C     GAS PHASE DENSITY
C
      REAL*8 FUNCTION RHOG(TF)
      IMPLICIT REAL*8 (A-Z)
      RHOG=353.4143816/TF
      RETURN
      END
```

```
C
C      GAS PHASE PRANDTL NUMBER
C
       REAL*8 FUNCTION PRG(TF)
       IMPLICIT REAL*8 (A-Z)
       PRG=CPG(TF)*RMUG(TF)/RKTHG(TF)
       RETURN
       END
```

```
C
C     LIQUID PHASE PRANDTL NUMBER
C
      REAL*8 FUNCTION PRL(TL)
      IMPLICIT REAL*8 (A-Z)
      PRL=4178.*RMUL(TL)/RKTHL(TL)
      RETURN
      END
```

```
C
C     GAS PHASE HEAT CAPACITY
C
      REAL*8 FUNCTION CPG(TF)
      IMPLICIT REAL*8 (A-Z)
      A=28.09
      B=1.965E-03
      C=4.799E-06
      D=-1.965E-09
      CPG=(((D*TF)+C)*TF+B)*TF+A
      CPG=CPG*1000/28.97
      RETURN
      END
```

```
C
C     GAS PHASE ENTHALPY
C
      REAL*8 FUNCTION HPRIME(T,YPR)
      IMPLICIT REAL*8 (A-Z)
      HPRIME=CS(T+273.15,YPR)*T+(YPR*2502300.)
      RETURN
      END
```

```
C
C     GAS PHASE VISCOSITY
C
      REAL*8 FUNCTION RMUG(TF)
      IMPLICIT REAL*8 (A-Z)
      RMUG=(1.458E-06)*TF**(1.5)/(TF+110.4)
      RETURN
      END
```

```
C
C     LIQUID VISCOSITY
C
      REAL*8 FUNCTION RMUL(TL)
      IMPLICIT REAL*8 (A-Z)
      A=0.09154996458
      B=-159.9864214
      C=-624.090532
      RMUL=1.0/(C+A*(TL+B)**2)
      RETURN
      END
```

```
C
C     THERMAL CONDUCTIVITY, GAS
C
      REAL*8 FUNCTION RKTHG(TF)
      IMPLICIT REAL*8 (A-Z)
      TB=TF*1.8
      A=1.0+(441.7/TB)*10.0**(-21.6/TB)
      RKTHG=1.972577346E-03*DSQRT(TB)/A
      RETURN
      END
```

```
C
C     THERMAL CONDUCTIVITY, LIQUID
C
      REAL*8 FUNCTION RKTHL(TL)
      IMPLICIT REAL*8 (A-Z)
      A=0.4955670305
      B=207.9173286
      C=-51654.23419
      RKTHL=A+(B/TL)+C/(TL**2.0)
      RETURN
      END
```

```
C
C     HUMID HEAT
C
      REAL*8 FUNCTION CS(T,Y)
      IMPLICIT REAL*8 (A-Z)
      CS=CPG(T)+Y*1884.
      RETURN
      END
```

```
C
C     Y PRIME SATURATION
C
      SUBROUTINE YSATPR(TI,YPS,PSAT)
      IMPLICIT REAL*8 (A-Z)
      THETA=TI/647.3
      DIF=1.-THETA
      A=-7.691234564*DIF
      B=-26.0802396*DIF**2
      C=-168.1706546*DIF**3
      D=64.23285504*DIF**4
      E=-118.9646225*DIF**5
      T1=A+B+C+D+E
      B1=1.0+(4.16711732*DIF)+(20.9750676*(DIF**2))
      B2=(1.0E+09*(DIF**2))+6
      BETAK=DEXP(T1/(THETA*B1)-(1.-THETA)/B2)
      PSAT=3208.234759*BETAK
      YPS=(PSAT*18.015)/((14.696-PSAT)*28.97)
      END
```